NUCLEAR ENGINEERING VOL. 6 NO. 58 MARCH, 1961

AEA Rationalization

REORGANIZATION OF THE U.K.AEA (see p. 95) is not the only evidence that the Authority has taken to heart the recommendation by the Select Committee (and others) to improve the collaboration between the various establishments under its control. There has, for example, been a marked change within the Research Group over the past 12 months and a much closer identification of much of the establishment's work with the Authority's general programme, without compromising the essential purpose of Harwell which is to do basic and advanced research into fundamental properties. This has come about not merely because of organizational arrangements such as management boards including representatives from other Groups but because of a new spirit prevailing in the establishment and the resurgence of the pioneering spirit which one associated with earlier days. Quite a significant fraction of the establishment's work is still, of course, associated with such projects as Nimrod which is quite distinct from, and indeed has virtually no connection with, nuclear energy exploitation.

Basic Research

The continuing need for basic research should be self-evident and indeed can be justified in many instances on quite straightforward economic grounds. For example, research which leads to an increase in burn-up of 10% of fuel for the 1968 power construction programme, would lead to a saving to the country of some £25 million. This assumes that no more Magnox reactors were built beyond the 5 000 MW programme and that their useful life was limited to 20 years, both of which assumptions are almost certainly pessimistic. Besides the direct economic returns we do not wish to be again caught as we were at Windscale, when quite suddenly it became appreciated how little we knew of one of the most basic materials in our whole programme, viz: graphite. There is, however, a danger in dotting the i's and crossing the t's for their own sake and the Winfrith establishment was beginning to savour more than a little of this type of operation. Desirable as it may be (if one has effort and money to spare) to know all there is to know about the physics of Magnox reactors there is little purpose in pursuing the matter when designs will be controlled by engineering and metallurgical considerations. There is a real danger that the AEA staff at Winfrith would have been permanently engaged on producing a mass of results which either were too late to influence design or alternatively could not influence reactor thinking because of the absence of an adequate say in future reactor policy.

Now that Winfrith is to be fused into the new Reactor Group the opportunity for the physicists and engineers to get back to working together, is at least nominally simplified. There are, of course, acute geographical problems and the task of really co-ordinationg the activities of four such widely dispersed establishments as Windscale, Risley, Dounreay and Culcheth remains formidable in the extreme. There is also, unfortunately, in the Authority (and it is not alone in this respect) something of an antipathy between physicists and engineers, and whilst Winfrith has to face the difficulty of changing its allegiance, Risley also must discard some deeply ingrained prejudices regarding scientists of southern origin. Winfrith has a lot to offer Risley which has become rather hide-bound and set in its ideas over the past few years and on its side Risley should be able to bring to the Winfrith establishment a sense of purpose which it was in danger of never achieving.

Key Appointment

An important appointment is that of Sir William Penney as deputy chairman with special responsibilities for co-ordinating research and development in the various Groups. The fact that he is also member for research should not be embarrassing as he is not the director of any particular establishment. It is hoped, however, that he will be allowed to do the job that has been assigned to him and that he will not again be diverted from this task by the necessity for taking a prominent part in nuclear disarmament talks.

The creation of a special Engineering Group at first sight may seem a little superfluous, particularly as the executive head is the same as for the Production Group, but its independent nature will be a benefit in two ways. Only by being unconnected with other Groups will it be able effectively to co-ordinate the Authority's contracting and buying arrangements which by unifying standards could see a considerable saving in outgoings and at the same time benefit the industry by establishing consistent design and manufacturing criteria. In its rôle as fuel element inspector responsible also for converting consortia proposals into manufacturing specifications it will go some way towards separating the Authority's twin functions of design advisers and judges.

No amount of Group or personnel shuffling will achieve the objectives intended unless there is a real will amongst the senior men in all Groups and all divisions of those Groups to work together and identify themselves with the national programme. The traditional rivalries so often initiated and fostered in all innocence but subsequently translated into schism must be abandoned. Atomic energy is not the most popular technology today and does not hold the popular appeal that it did a few years ago. The greatest enemy, however, to continued progress is not external opposition but internal strife. It is also not a bit of good establishing the precedent of shuffling the Groups around every twelve months. Changes create an atmosphere of uncertainty and hinder legitimate work. A period of stability is now required with everyone rowing the boat in the same direction.

Pressure Vessel Codes

THE wind of change was certainly blowing through the Institution of Mechanical Engineers towards the end of their Symposium on Pressure Vessel Research Towards Better Design (p.123) but unfortunately, as time wore on it became clear that this was a local eddy rather than a steady trade wind moving towards something definite. There is little doubt that the whole meeting was convinced that the time had come to change the existing codes covering pressure vessel design but it dispersed without any clear indication of the form which new codes should take or how the change should be made. Indeed, it was tacitly assumed by all, that any changes were bound to take a great deal of time and there was very little that could be done about it.

It is ironic that in this country where the codes are not regulatory the system is, in practice, as a result more inflexible than if they were. If a Ministry had the definite responsibility for enforcing regulations then it would be quite straightforward to bring pressure to bear upon it and something would be done; the industry would no doubt go to great trouble also to ensure that it were done speedily. Basically, however, the matter is in the hands of industry itself and this seems to be the stumbling block.

In view of the importance of the meeting, not only technically but also commercially, it was surprising to find so few of the senior members of the Institution present (with, we hasten to add, some notable exceptions). One gained the impression that stress analysis and the evaluation of safety criteria were subjects for the young and not for the established engineers who were content to rely on the old rule-of-thumb methods and shrug off the economic disadvantages this brought us in competitive exports. The absence of a hard core of leadership able and determined to thrash out a new approach to pressure vessel construction was most marked.

Whilst Lloyds' Register made important contributions to the meeting insurers, as such, were conspicuous by their silence and it is the insurers who, at present, are the final arbiters. In view of the very few failures that have occurred in the past, one can understand the reluctance of guarantors to change existing codes which have worked so well, but the evidence, particularly concerning brittle fracture where existing codes cause pressure vessels to be designed less safe than need be, should provide them with a vigorous incentive to see changes made.

Not everything is known about stress concentration factors nor the exact significance that must be attached to transition temperatures, creep and the like but this is no excuse for not modifying codes known to be outmoded, proved to be over-restrictive and shown to lead to less safe structures than could be designed. It is not, of course, necessary that there should be one code for all pressure vessels regardless of size, thickness, pressure, number and size of branches, etc. What is needed in this age of transition is a flexible code able to accommodate new findings, and develop with the technology and a new spirit amongst customers, insurers and contractors to promote and accept innovations based on modern research and thinking.

The SL-1 Accident

CONFRONTED last month with only the bare account of the immediately obvious aspects of the SL-1 accident, in which three men working inside the containment building of the former ALPR at Idaho Falls were killed, we hesitated to make comment. It is still perhaps a little premature to express definite opinions on the subject but one cannot ignore the implications of the interim report on the accident, prepared by the Board of Investigation of the AEC and published on February 2. This makes sorry reading.

It is clear that the reactor rapidly diverged and built up a pressure of explosion intensity, the blast from which killed two men immediately; the third man died within about two hours as a result of an injury to the head. Preliminary calculations suggest the reactor generated about 50 MWs of energy, producing a pressure within the unsealed reactor vessel of several hundred psi. Exactly why the reactor diverged is not known yet and a complete reconstruction is probably not possible. There is, however, sufficient history of operational problems resulting either from fundamental aspects of the design or features which had developed during running at power, which lead to the conclusion that any running of the reactor was hazardous. For example, in order to reconnect a control rod to its drive (the operation that is believed to have been taking place when the accident occurred) it was necessary to lift, manually, the control rod by a limited amount; exceeding the limit would result in reactivity being added and in the case of the central rod could result in criticality even when the core was fully poisoned; control rods had been sticking so that even under scram operation they had to be motored in and required manual assistance when they were withdrawn. The boron strip poisons attached to the fuel elements had been distorting, and removal of elements from the central region was difficult; furthermore, boron was being lost from the core and the reactivity of the reactor was greater than it should have been. When further cadmium strips were added to the core to increase the shut-down margin these were encased in 2S aluminium rather than the high temperature corrosion resistant nickel-alloy, and they were less effective than expected. The reactor had been shut down to allow the insertion of 40 cobalt flux measuring assemblies into the channels and for certain minor modifications to the reactor auxiliaries and it was following this that the crew of three was reassembling the control rods prior to start-up.

A possible sequence of events is that during the shut-down boron held in suspension or attached to the core settled out into the bottom of the vessel thus increasing the reactivity of the core, and then in attempting to raise the control rod the necessary few inches for attachment to the drive excessive force was applied to overcome the stickiness; the rod jumped up, the reactor diverged, steam pressure ejected the rod and the explosion occurred.

Whether the above explanation is correct or not is really beside the point. The tragedy is that the reactor was being used even when it was known that a number of things were working improperly. The AEC has instituted an immediate inquiry into the method of assessing the safety of reactors and administering their operation. This is clearly a matter of urgency. The Windscale accident resulted primarily from an imperfect understanding of fundamental physical phenomena but this is not the case with the SL-1 which on present evidence is a real blot on the escutcheon of nuclear energy.

World Digest

Progress at Hinkley Point where No. 1 reactor vessel was recently successfully pressure tested.

International

Countries to receive direct IAEA technical assistance during 1961 include Argentina, Brazil, Ceylon, Greece, Iceland, Indonesia, Israel, Korea, Mexico, Morocco, Pakistan, Philippines, Sudan, Thailand, Turkey, and Yugoslavia. Each country will be visited by experts to advise on certain nuclear problems (the total number of experts being sent is 31) and 13 of the countries are to receive nuclear equipment worth a total of $191 200.

Co-ordination of all energy policies of European Community countries is being considered by the Council of Ministers of the European Coal and Steel Community. A working plan has been drawn up by a group representing Euratom, the Common Market and ECSC.

An international atomic industrial forum composed of all national and regional forums should be established, suggested Mr. Sterling Cole, director general of the IAEA at the recent U.S.AIF conference in San Francisco.

Criticality control in chemical and metallurgical plant is to be the subject of an international symposium at Karlsruhe, May 2-5. Organizers are the ENEA in collaboration with Kernreaktor Bau-und Betriebsgesellschaft m.b.h.

Fourteen countries are to be represented on an IAEA committee to draw up a draft international convention on civil liability for nuclear damage.

Safeguard principles and procedures as discussed at last year's general conference of the IAEA have been approved, with one modification, by the Agency Governors on a majority vote. The amount of source material exempted from the safeguards has been increased.

United Kingdom

Impatience grows over the Government's delay in a decision on the construction of a nuclear propelled ship. The Minister of Transport is being constantly harried in the House of Commons and, outside, industry looks on with frustration at the steps being taken in Germany, where a contract has just been signed with Euratom for an OMR marine design study and a shipbuilding company has announced it intends to buy a reactor to install in a tanker to gain early operating experience. Further, another Euratom contract is shortly to be signed either with a French or Italian marine group. In the meantime, all the Minister of Transport can announce is that the technical committee examining the tenders will shortly call a meeting to draw up a report following the completion of its scrutiny.

A symposium on experimental rigs is to be held at Harwell during April. Its purpose is to enable the AEA and industry to exchange information on equipment and apparatus built for testing reactor and plant components.

A decision is still awaited over the placing of government grants for university reactors. It is understood that it has been decided that London University will have only one reactor and a study is now being made to find out which reactor type (if there is one) would meet the requirements not only of the appropriate nuclear engineering departments, but all other departments in the university likely to make use of a reactor. The study, it is understood, is being made by a committee appointed by the Master of Churchill College, and consisting of representatives of the AEA and Manchester and Glasgow Universities.

The British Hydromechanics Research Association is holding on April 17-19, at Ashford, Kent, an international conference on fluid sealing.

Ratings of 100kW have been achieved with safety on the Jason at Langley, Slough. The reactor is designed for a 10kW output and the increased ratings were brought about as part of a development programme being undertaken by the Hawker Siddeley Nuclear Power Company for advanced Jason types. At the same time useful information as to the safety of the reactor was provided. Three runs at 100kW were made, each one of about 20 minutes' duration. The cooling supply was as for 10kW. In two of the runs the coolant supply was completely interrupted. When no attempt was made to compensate for the rise in temperature the power quickly fell and the reactor stabilized out at 10kW. When the control rods were withdrawn to compensate for temperature rise the power remained steady at 100kW until they were fully withdrawn then fell to about 20kW. For the final run the cooling supply remained at a constant 4 gal/min. The reactor was then scrammed from 100kW and the rapid removal of heat by air convection was observed.

The European American Nuclear Data Committee is meeting at Harwell in July to discuss fundamental measurements.

Reorganization of the AEA

THE creation of the new post of deputy chairman and of a new Group and the modification of the Development and Engineering Group are the principal changes in the re-organization of the AEA which are to take effect from April 1. The purpose of these changes is to improve co-ordination and efficiency within the Authority, and they stem from the recommendations of the Select Committee which reported on the Industrial Group, in the first instance, in July, 1959. The deputy chairman—who will be Sir William Penney—will be responsible for scientific and technical co-ordination. One new Group is the Reactor Group; it will take over the work of the Development and Engineering Group concerned with the development of prototype reactor plant. It will also embrace Winfrith, which is transferred from the Research Group. Headquarters of the Reactor Group will be at Risley and Sir William Cook, at present known as Member for Development and Engineering, will become Member for Reactors. Mr. R. V. Moore, a D. and E. deputy managing director, becomes managing director of the new Group. The responsibilities of the D. and E. Group for the design and construction of plant, works and buildings will be transferred to a new Engineering Group, which will also take over from the Production Group its responsibilities for the design and inspection of fuel elements for production purposes. Head of the Engineering Group will be Sir Leonard Owen who at the same time remains in overall charge of Production. His title will be Member for Engineering and Production. Managing directors of the Production and Engineering Groups will be Mr. J. C. C. Stewart and Mr. J. B. W. Cunningham.

The Reactor Group's principal establishments will be Dounreay, Winfrith, the experimental portion of Windscale, Culcheth and the laboratories at Risley moved from Capenhurst. When the Windscale AGR is complete, Production Group will operate it for the Reactor Group. Sir Basil Schonland retires and Dr. F. A. Vick becomes director of the Research Group.

A plea for the AEA to encourage the development of an exportable reactor was made in the House of Commons recently by Mr. John Eden, Member for Bournemouth, West. He was moving a resolution urging the Government to "maintain the nuclear power programme at a level that will encourage the development of manufacturing experience and capacity, and provide the best possible prospects for exporting British design, products and skill." The resolution was adopted, after debate, without a division.

A Parliamentary Secretary has been appointed to the Minister for Science. He is Mr. Denzil Freeth and will be responsible for answering questions in the House of Commons related to the office of the Minister for Science. Because the present Minister (Lord Hailsham) sits in the House of Lords such questions have previously had to be dealt with by other Ministers who sit in the House of Commons.

One of Calder Hall's four reactors has just been closed down for maintenance and change of fuel after 12 months of continuous operation. During this period the reactor was used to generate electricity at full load for 95·6 per cent. of the time. The period not on full load was accounted for by the following :—

	%
Experimental work	2·5
Scheduled maintenance of ancillary equipment	0·7
Unscheduled blower maintenance	0·6
Unscheduled maintenance of other equipment	0·4
Special fuel element tests	0·2

A seismic research programme on a large scale is to be carried out by the AEA in connection with the detection and identification of underground nuclear explosions. It will be financed by a sum of £350 000 voted by the House of Commons. Staff will be recruited from AWRE, Aldermaston.

Australia

A new high-grade uranium ore deposit has been found at Rum Jungle, in the Northern Territory. It is said to be at least comparable with the total amount of ore already mined there—up to June, 1960, over 360 000 tons of uranium and uranium-copper ores have been treated there and the stockpile of these ores at that time was over 190 000 tons. The government's policy over the working of the new deposit will be decided in relation to the problems of the uranium industry as a whole and the anticipated reduction in world demand for the metal.

Processing fuel elements incorporating beryllium is the subject of research at Lucas Heights, states the eighth annual report of the AEC, 1959-60, claiming that such work is not being carried out in any other country. The commission is concentrating its materials research on beryllium and beryllium compounds as part of the HTGCR development programme.

Canada

Ontario Hydro-Electric Power Commission estimate 14% of the Provincial power load will be nuclear by 1970. This represents 1 618 MW. Of the remainder, 48% would be hydro-power and 38% from coal-fired power stations. The proportion of nuclear power is estimated to increase to 34% or 7 218 MW by 1980. Experts have estimated up to a further 5 000 MW of nuclear power in the rest of the country by 1980, for a total of about 12 000 MW, or about 20% of the estimated 1980 power load.

Czechoslovakia

The Institute of Nuclear Research, Prague, is to carry out research for the IAEA to ascertain the physico-chemical requirements for the disposal of low activity liquid wastes in soil. It is the 100th research contract awarded by the IAEA to institutions and laboratories in member States since 1958.

Denmark

The hot cell facility under construction at Riso will cost about kr 15 million (about £770 000) according to the 1959-60 report of the AEC. Work started on the facility early last year after following the recommendations of the U.K. consulting engineers, Atkins and Partners. It is scheduled for completion by 1962. Because of the lack of suitable hot cell facilities at Riso it was necessary to arrange for the examination of specimens to be irradiated in DR3 for the Dragon project to be carried out at Studsvik, Sweden.

France

Twenty kilograms of enriched uranium have been sent from the United States for use in the development of the prototype submarine nuclear propulsion plant to be built at the Cadarache research centre. This is the first consignment since an agreement for the supply of 440 kilograms of enriched uranium became effective in July, 1959. At about that time the authorities were considering the construction of a submarine reactor using natural uranium and heavy water. With an increase in their knowledge and experience they now feel they can successfully tackle a reactor of a more compact design. The first sea-going nuclear submarine, to be known as the Q 244, will be built at Cherbourg and will be of French design and construction throughout.

Consumption of electricity increased from 64 545 million kWh in 1959 to 72 000 million in 1960, states the latest annual report of the EDF. Hydro electric production increased from 32 583 to 40 350 million kWh, while thermal production was reduced from 31 924 to 31 800 million kWh. There were increases in the importation and exportation of electricity.

West Germany

The Emden shipbuilders, Rheinstahl Nordseewerke G.m.b.H., have plans to buy a PWR from the U.S.A. for installation in a tanker.

Deutsches Atomforum is being made into a legally constituted association with headquarters at Bonn. At the same time the four foundation bodies of the forum are being dissolved—Physikalische Studiengesellschaft, Arbeitsgemeinschaft Kerntechnik, Deutsche Gesellschaft fur Atomenergies and Verein Atom fur den Frieden.

The AEG-Argonaut at Gross-Welzheim-near, Kahl, has gone critical. Initial experiments with this reactor will be related to the proposed IGE-AEG BWR plant with superheater.

Following the Government's acquisition of a controlling interest in GKSS (last month's "World Digest") Euratom has signed a contract to participate in the GKSS-Interatom OMR marine propulsion design study, started early 1959. Under the contract terms Euratom is to have a 40% share in the project and will contribute up to DM4·48 million towards it. This participation will be retroactive and will cover the whole design phase of the reactor up to and including the completion of working designs, which is expected at the end of this year. Euratom will have an option on participating in any construction work that might follow. Tenders for a 22 000-ton vessel have in fact been invited from German shipyards by the GKSS. Construction of the vessel would not start at the earliest before 1962 and would take an estimated 2½ years to complete.

A Triga Mark II is to be installed at the Institute for Inorganic and Nuclear Chemistry, Johannes Gutenberg University, Mainz. The Federal Ministry for Atomic Energy is to provide DM1·53 million towards its cost and a further DM3·3 million for associated laboratory and other facilities. It will be the first Triga bought in Germany.

India

Prime Minister Nehru at the opening of the CIR, Trombay. Sphere in the background is the emergency water storage tank.

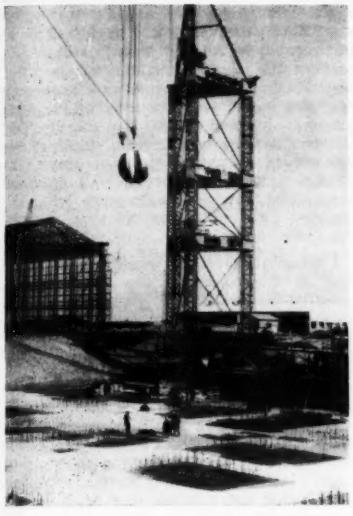
Construction of a plutonium recovery plant at Trombay is scheduled to be started in March. It is due to be completed and ready for regular operation by early 1963. It will be used to process irradiated CIR elements.

An agreement with Russia for co-operation covering natural uranium and fast power reactors is to be signed this year. It is believed that chief interest is in the 100-150 MW class. The Soviet Union is not tendering for the 300 MW Tarapur project.

Indonesia

Two reactors are to be supplied by the Soviet Union. One of them, a $2 million facility, is to be sited at Djakarta, the capital, and the other, a $200 000 reactor, is for the Gadjah University. It is understood that negotiations are under way for a Triga.

Japan



Live pigeons and streamers were released from the paper sphere suspended over the Tokai Mura site as part of the Shinto ceremonies recently held to mark the start of the second building stage.

Netherlands

An experimental physics block is to be built at the R.C.N. research centre, Petten. It will house the LFR and Krito, a critical assembly. The building will be named after Enrico Fermi.

Norway

Nora, the heavy-water zero-energy reactor at Kjeller, is to be made available to the IAEA for a joint reactor physics research programme. Work will be controlled by a five-man committee comprising two nominees each from Norway and the agency and a mutually appointed chairman. The U.S.A. is to supply fuel enriched to 3% towards the programme (it will be a fuel loading used in the development work for the *Savannah*) and Norway will provide a core of natural uranium and another enriched to 1.7%. Construction work on Nora is nearing completion and criticality is expected to be achieved around May 1.

The Institutt für Atomenergi has signed an agreement with the United Arab Republic for the exchange and training of personnel and the exchange of information. The Institutt is also to help with the construction of a radioisotope laboratory in Egypt.

Pakistan

Talks have been held with the German Ministry of Atomic Energy relating to the possibility of Germany contributing to the development of nuclear energy in Pakistan.

Plans for the N.S. *Savannah*

It is reported from Germany that the N.S. *Savannah* is expected to call at Hamburg this summer and the Studiengesellschaft für Kernenergieverwertung in Schiffbau und Schiffahrt is to arrange a meeting on board. A special docking licence will be required but in view of last year's successful visit by the U.S.S. *Triton* to Bremershaven (also to be visited by the *Savannah*) this is not expected to present any problems. This report is the first indication of any definite plans being made for the reception of the *Savannah* during her proposed world voyage. There has been talk that she might visit Britain in the September, but so far the safety formalities involved have not been settled. The U.S. authorities themselves have made no announcements about the voyage. Start up and sea trials are expected to take place during the next two or three months. At present non-nuclear tests are being undertaken and the public safety hearing fixed for February 1 has had to be postponed until March 6 to allow these to be completed. Officially the hearing is for the purpose of giving a green light to the start-up, on which the AEC Reactor Safety Advisory Committee have already advised that the ship's reactor should not be operated at more than 7 MW (10% of the total maximum capacity).

South Africa

New agreements have been reached for the supply of uranium oxide to the U.K.AEA and U.S.AEC. Purchases will be made direct by the two organizations instead of through the Combined Development Agency, and in the case of the AEA deliveries will be stretched out to last until 1970 instead of finishing in 1966. The total tonnage to be delivered — 28 350 — remains unchanged. Under the new agreement the U.S.AEC will buy 18 900 tons between January 18, 1961, and December 31, 1966, while the U.K.AEA in the same period will buy 3 497 tons. The remaining 5 953 tons will be supplied between 1967 and 1970.

Production would stop at some uranium mines as the result of the new trading arrangements (see above) according to the chairman of the Atomic Energy Board. Steps would be taken to ensure this caused as little disruption as possible, he continued, particularly as regards to the employment of workers at uranium installations. He also reported that under the terms of the new contracts the fixed price of uranium oxide would be a little lower than the average price paid in 1960. He said the Board was convinced that the new arrangements would benefit the country, particularly as they meant the industry would be kept going until 1970.

West Africa

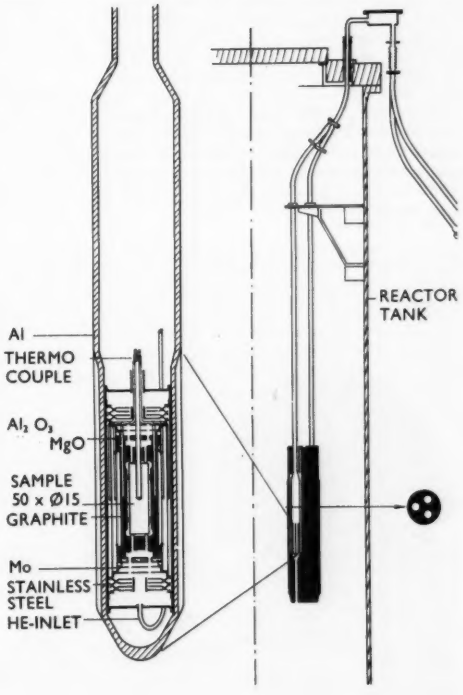
A preliminary assistance mission of the IAEA is to visit Ghana this year. Some of the mission members will also visit Dahomey, Liberia and Nigeria, which are not yet members of the Agency.

Turkey

The 1 MW AME reactor under construction at Kucukcekmece, Istanbul, should be completed and ready for operation by the autumn, according to the first published report of the AEC, covering the period 1957-60. Also during 1961 a, sub-critical assembly is to be established, with the help of the IAEA, at Ankara University.

Sweden

The R2 at Studsvik is to be used for research in connection with the Dragon project and three special test loops are to be built for this purpose. They will be placed in parts of the reactor where the neutron flux is calculated to be $10^{14} n/cm^2 s$. The emission of fission products from specimens from Dragon fuel elements will be studied in the loops at temperatures of up to 2 000°C. Helium gas will circulate through the loops at a rate varying between 1 $cm^3 s$ and 500 $cm^3 s$. The loops will be designed and built by AB Atomenergi and they are to be completed by October, 1962. Their cost will be about KrSw 1 million (about £70 000). The agreement covering the construction of the loops and the use of the reactor also provides for the use of R2 personnel for two or three years.



U.S.A.

A beryllium oxide moderated, helium cooled reactor is to be built at Idaho Falls to provide data for marine propulsion units. Fuel will be a mixture of uranium and beryllium oxide. The core is planned to be about 75 in long by 24 in in diameter, surrounded by a beryllium oxide reflector 7 in thick. Design will allow for helium outlet temperatures of up to 1 500°F and pressures as high as 1 120 psia. Maximum power level will be 10 MW(th). Construction of the reactor, to be known as BORE, is scheduled to start in the summer. Responsible for its design, building and test operation is General Atomic.

U.S.S.R.

Three CERN physicists are spending six months at the Dubna research centre as part of an exchange agreement reached between CERN and Dubna last year. Three Soviet scientists have already spent six months at the Meyrin laboratories and in January of this year two more went there. The CERN personnel now in Russia are Dr. W. H. V. Cottingham, who joined CERN from Birmingham University, Dr. E. Fischer, of Germany, and Dr. M. Schneeberger, of Switzerland.

The court decision invalidating the provisional permit for the construction of the Enrico Fermi plant placed the whole reactor programme in jeopardy, comments the AEC in its 1960 report to Congress. If the decision was not revised by the Supreme Court (to which an appeal has been made) or clarified by new legislation, it could be a serious blow to the progress of power reactor developments, adds the report.

Costs of $47·2 million were incurred during the three months ended September 30, 1960, on civilian nuclear reactor projects under active design or construction for installation in the United States, reports the AEC. Of the total, $40·7 million represented costs for 22 electric power prototypes and experiments and $6·5 million for research and test reactors and the *Savannah* propulsion plant. Of the $40·7 million, $21·9 million represented costs to publicly and privately owned utility companies; the remainder to the AEC. Total estimated costs for all civilian projects now under way are $942·6 million.

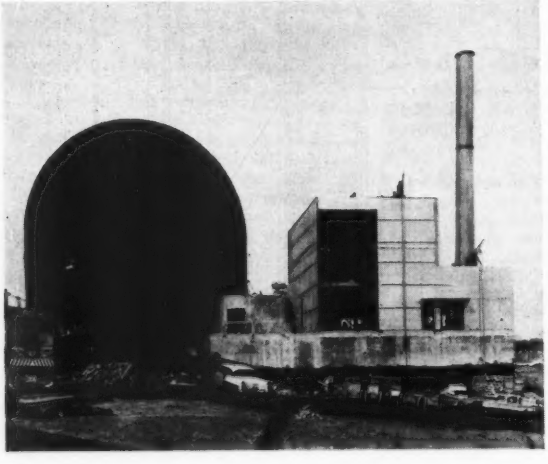
Royalties are now payable by foreign corporations and nationals on AEC-owned foreign patents, following a change in the Commission's policy. Up to now all AEC-owned patents have been free of royalties. Payment will be charged only in those countries which charge the U.S. government or U.S. citizens royalties. Elsewhere the AEC will grant free licences, although if a country has no fixed policy in this matter the AEC will make necessary adjustments depending on the circumstances. The change in policy is designed to establish a more equitable arrangement for the participation of U.S. industry in overseas nuclear energy programmes. While this could mean that U.S. industry will obtain more overseas work due to the reluctance of foreign companies to pay royalties, it could also lead to foreign companies relying less on American inventions and techniques.

A chain reaction momentarily occurred in a cell at the Idaho Chemical Processing Plant leading to a rise in the radiation level. Staff were evacuated but none suffered from any significant exposure (a study of film badges revealed maximum exposures of 55 mr). They returned five hours later.

America's twenty third nuclear submarine has been launched. She is the U.S.S. *Sam Houston* and is the seventh submarine capable of firing the Polaris missile at sea. Recently commissioned was the fifteenth nuclear submarine, U.S.S. *Shark*.

Rhode Island Atomic Energy Commission is to buy a 3 MW(th) open pool reactor from General Electric. It will be installed at Fort Kearney.

Atomics International are to undertake for the AEC the conceptual design of an OMR system for a 50 MW power plant. An invitation has gone to utility companies to indicate their interest in the building of such a plant, which the AEC would like to see in operation by 1964.



Atomics International report construction of the Piqua plant is proceeding smoothly. Operation of the reactor is due to start in the autumn.

The last phase of testing for the Heat Transfer Reactor Experiment No. 3 (HTRE-3) at Idaho Falls has been completed. In operation since September, 1959, it is the third in a series of facilities operated by General Electric to verify aircraft nuclear propulsion reactor design factors and operating characteristics. With it two jet engines were for the first time run simultaneously on nuclear energy, and last November start up of the turbines was for the first time achieved on nuclear power alone. Previously the engines had been started up with chemical fuel and were transferred to nuclear power when they reached the normal operating range. The reactor, which was designed in a horizontal configuration as would be required for flight purposes, used concentric ring metallic fuel elements and a solid moderator material and was capable of operating at approximately 2 000°F. It has now been shut down in preparation for tests with more advanced reactors.

Columbia University, where the first splitting of the atom in the United States occurred 22 years ago, has just bought a Triga Mark II. It will be the first nuclear reactor to be installed and operated in New York City.

Operation of Dresden is expected to be resumed this spring when new control rod drives will be installed. Failure of one of the drives caused the reactor to be shut down last November. Stress corrosion cracking of the stainless steel used in the drive tube was reported. The same material, 17-4PH stainless steel, will be used in the modified parts "with more recently developed techniques for heat treatment and quality control." General Electric report that other GE reactors, such as the VBWR at Vallecitos and the Kahl reactor, Germany, will have some parts replaced as a result of the Dresden experience. Rod drives of the same steel already installed in the *Savannah* and planned for the Big Rock reactor are being re-examined.

A symposium on uranium carbides as reactor fuel materials is to be held by the AEC on April 4. Industry will learn of the research undertaken by the Commission in the development of these compounds.

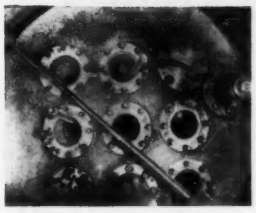
Deliveries of nuclear energy products made by private industry during 1959, *including those to government agencies and overseas, were worth a total of* $244 858 000, *report the Bureau of Census. In* 1958 *they were worth* $161 762 000 *and in* 1957 $99 614 000. *The* 1959 *total included* $19 989 000 ($17 099 000 *in* 1958) *worth of primary vessels and tanks;* $5 404 000 ($7 481 000) *worth of control rod drive and mechanisms;* $15 933 000 ($15 284 000) *of control instrumentation;* $27 233 000 ($13 799 000) *of heat exchangers and condensers;* $54 845 000 ($23 873 000) *of fuel elements and control rods ready for use and* $28 928 000 ($25 186 000) *of radiation and detection devices. The other products which are covered by the total include radioisotopes, instruments using radioisotopes* ($8.8 *million in* 1959 *compared with* $3.8 *million in* 1958) *and income from irradiation services and the conversion of enriched uranium.*

The SL-I Accident

THE most likely cause of the SL-1 accident at Idaho Falls (reported in last month's "World Digest") was a nuclear excursion resulting from the movement of the central control rod. This is the view of the investigation committee as contained in its preliminary report.

The report goes on to say it was known that a variety of conditions had developed in the reactor which might have contributed to the cause and extent of the incident. Some of these had their origin in the reactor design and others in the cumulative effects of reactor operation.

In reconstructing the events prior to the incident, the report assumes that the shift supervisor, his operator-mechanic assistant and an apprentice trainee (who were all killed) were on top of the reactor engaged in reassembling the control rod drive mechanisms. The reactor had been in operation for just over two years when on December 23, 1960, it was shut down for maintenance purposes. The intention was to restart it on January 4, 1961.



(Above) Still from film of the SL-1 top after accident. (Right) General view taken four days after accident. It shows the pressure vessel head. In the foreground are steel punchings with some gravel and boric oxide which formed the dry-mixture shield above the reactor head.

The only work planned for the reactor core was the insertion of 40 cobalt flux measuring assemblies into fuel element channels of one quadrant of the core. This necessitated the removal of the control rod drive assemblies, which was in fact carried out during the early hours of January 3.

Installation of the flux measuring assemblies was accomplished by the day shift and the next two shifts were assigned the tasks of reassembling the control rod drives and preparing the reactor for start up. At about 9 p.m., January 3, the alarm signal was sounded.

It is known that the reassembly operation involved the manual lifting of the control rod blades, a maximum of 4 in. Testimony before the investigation board indicated that the two senior men killed had performed this task some four times before and had been specifically trained for it.

For editorial comment see page 94.

Correspondence

Sir,

The article by Mrs. Hill in your February issue on "Plutonium for Propulsion Reactors" propounding the possibility of near-perpetual operation makes exciting reading. The attractions of a limitless fuel life for a reactor in a ship, of course, need no emphasis but the reactivity analyses would appear to be based on the assumption that the Pu^{240} content of extracted plutonium will be reasonably constant. So far as present plans are concerned the Generating Board, it seems, is not proposing to cycle the fuel elements in the Magnox reactors; there will thus be at least a factor of three in the burn-up between the most highly rated and the most lowly rated elements, and this will be reflected not only in the plutonium concentration in the spent fuel (which is immaterial) but also in the Pu^{240} proportion.

In view of the small effective batch size during spent fuel element processing, consequent upon avoiding critical geometries, the opportunity for gross mixing would appear to be small; even with true continuous separation the output concentration must be expected to follow closely that of the individual elements fed to the head-end.

What steps then are being taken to segregate elements discharged from a reactor before and during processing so that fuel of a defined Pu^{240} content can be used in the manufacture of future elements? Have arrangements been made (and on a production basis is it even possible) to determine the Pu^{240} content of a given batch?

If, however, one must assume that the plutonium raw material for enriching fuel elements will contain a random concentration of Pu^{240} what influence will this have on the hot spot factors, fine structure flux, and overall fuel life in a heavy water moderated, steam cooled reactor of the type discussed?

R. N. Quartano.

Sir,

Your correspondent raises some very interesting points on the supply of plutonium for marine reactors. I should like to make the following remarks.

1. The importance of non-uniformity of Pu^{240} concentration in the supply from production reactors depends on the relative sizes of the marine reactor loading and the production reactor output. For example, let us assume that the plutonium yield from the present production reactors is of the order of 250 kg per core loading. Then if the required loading for a marine reactor is say, 50 kg, it should be possible to obtain a reasonably constant Pu^{240}/Pu^{239} ratio by careful selection of fuel from given zones of the production reactor. If, on the other hand, the marine reactor requirement is of the same order as one production core yield, one may have to wait for several production cycles in order to obtain fuel of the correct quality. Alternatively, one could deliberately vary the Pu^{240}/Pu^{239} ratio in different zones of the marine core in order to obtain some initial power flattening. The systems we are considering at the moment would require between 150 and 250 kg of plutonium per core.

2. Since our fuel element clusters are not immersed in moderator and are fairly "black" to incoming neutrons, we do not anticipate large changes in hot spot factors or fine structure due to small random variations in the Pu^{240} content.

3. It is clear from Fig. 4 of my paper[1] that the total plutonium loading for a given life increases with increasing Pu^{240} content. Since the present cost of plutonium does not vary with Pu^{240} content, one would always design for Pu^{240} fractions as close to the lower bounding line of Fig. 4 as possible. Variation in Pu^{240} content about the design point will thus lead either to cores which are unable to meet the lifetime specifications but may cost less to operate, or cores which will meet design specifications but are more expensive. The order of magnitude of the effect is that a change in Pu^{240} content from 20% to 25% Pu^{240} would increase the fuel cost by about 10%.

(Mrs.) J. Hill.

Sir,

It is with some concern that we note the apparently growing habit of using the phrase "The English Electric Group" to describe the consortium which is building Hinkley Point and Sizewell nuclear power stations for the Central Electricity Generating Board.

I would be obliged if you would arrange, in future, always to use the consortium's proper title which is "The English Electric, Babcock and Wilcox, Taylor Woodrow Atomic Power Group" in referring to our activities.

E. C. Roberson.

[We also apologize for a recent reference to "United Power Constructions"—the G.E.C.-Simon Carves and APC joint company. The correct title is, of course, United Power Co., Ltd.—Ed.]

[1]Page 66, February, 1961.

TRENDS IN DESIGN

A Comparison of Main Parameters in British Nuclear Stations

An attempt is made to compare some of the major parameters of British nuclear stations (including Calder Hall).

NEARLY five years have elapsed since the commissioning of Calder proved that the gas-cooled graphite reactor was a practical proposition for the generation of electricity, although, admittedly, ideas on the economics have required some modification. Nevertheless, since then, a vast amount of work has been expended in the design of large gas-cooled reactors, and it would appear an appropriate moment to review progress in this field. To this end, strip charts have been plotted for easy comparison of the significant parameters of a number of designs, and these appear on the adjacent page. The selection has been limited to stations in Britain so that, with the exception of Hunterston, they are—or will be—the property of the CEGB. Calder has been included for reference.

Inferences

Before drawing conclusions from the charts, it is important to bear in mind that none of the stations is yet in operation, with the exception of Calder, which is optimized for plutonium production, not electrical output. The figures given can only be regarded as reasonable expectations. Furthermore, the list is not complete, certain of the Sizewell parameters being not available.

Some of the charts are matters of record only, and the only inferences to be drawn are rather drearily obvious. Considering Figs. 1, 2 and 3, for example, it does not require much detective ability to decide that, if the thermal output falls while the electrical output rises, the overall thermal efficiency must be higher. The only point of interest is that, as shown in Fig. 3, the thermal efficiency reaches a maximum for Dungeness, and then falls for the next station, Sizewell. This doubtless reflects the designer's viewpoint that thermal efficiency is not the sole consideration; support for this assumption is provided by the slight drop in thermal efficiency for Hinkley Point as against its immediate predecessors—both Hinkley and Sizewell designs being by the same consortium.

Thermal Efficiency

It is not always realized that with a nuclear station, thermal efficiency is not the only factor of importance in a design. In a coal-fired station, where the annual value of coal burned in a boiler may be comparable with the capital cost of the boiler, thermal efficiency may—within limits—be the most important parameter. In a nuclear station, this is not the case. The significant figure is the overall cost per kWh sent out and some two-thirds of this —in some cases as high as three-quarters—is accounted for by capital charges, so that optimization for minimum overall cost of generation may make thermal efficiency a secondary consideration.

The slight drop in thermal efficiency of Hinkley Point is reflected in the chart of gas temperatures (Fig. 6). The Sizewell figures are not available, but it is reasonable to suppose that they are slightly lower than Dungeness. Metallurgical considerations have set a limit to any significant increase in outlet temperatures with Magnox canning; taking hot channels and transients into consideration, there is a limit beyond which the prudent designer will not go.

Steam Conditions

Figs. 7 and 8 are worth looking at with a speculative eye. There has been very little change in steam temperatures—which would be expected, considering the consistency in gas outlet temperatures—but the steam pressures vary a little, doubtless reflecting designer's ideas on permissible wetness at the turbine exhaust. The exception is, of course, Dungeness, where the notable peak in steam pressure is apt to give a false impression unless it is remembered that at this station the H.P. steam is used for blower drives by means of back pressure turbines; the main sets operate on low-pressure steam alone.

Fig. 10 is of interest in showing the gradual improvement which has taken place in the net electrical output per tonne of uranium. It will be noted that 1 MW/tonne has not yet been achieved, but the last three stations come within measurable distance of this figure.

The amount of graphite required per net electrical MW is shown in Fig. 12. Improvements in knowledge of nuclear physics and progress in the minutiae of the detail of core design (including reduction in lattice pitch) have been largely responsible for this although, since the chart is plotted for net output, the situation is a little obscured by considerations of thermal efficiency. It is interesting to note, however, the way in which the weight of graphite comes down from the Calder figure in two steps.

Costs

Neither capital costs nor cost per unit sent out have been plotted. Figures given by Sir Christopher Hinton* for Berkeley, Bradwell, Hinkley Point, Trawsfynydd and Dungeness indicate a capital cost (£/kW s.o.) of 160, 159, 133, 123, and 110 respectively. These, of course, are the costs as estimated by the CEGB; they do not represent contract prices, since the proportion of costs added for particular sites are not necessarily the same, so that they do not give a strictly fair basis of comparison between the designs of the various consortia. Contract prices, on the other hand, do not necessarily represent total capital costs.

It is also considered preferable not to plot estimates of generating costs per unit. While very close estimates have been made of these figures it is once more emphasized that no station is yet in operation and that to attempt to draw further comparisons based on estimates alone would serve very little purpose.

* Sir Christopher Hinton. "The Evolution of Nuclear Power Plant Design." Paper read at the Royal Society's Tercentenary Celebrations, July 20, 1960.

British Station Comparisons

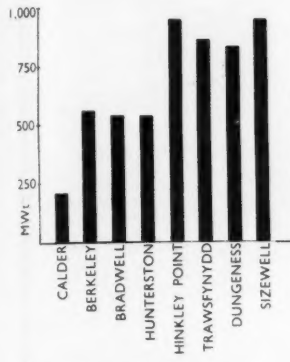


Fig. 1.—Gross thermal output per reactor.

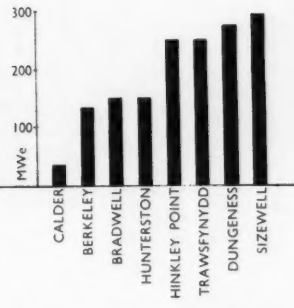


Fig. 2.—Net electrical output per reactor.

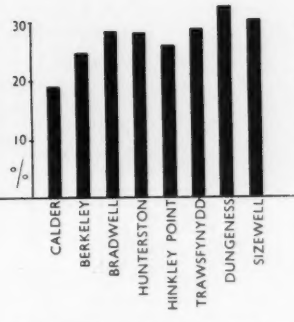


Fig. 3.—Overall thermal efficiency of station.

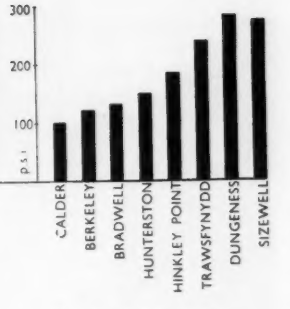


Fig. 4.—Gas pressure.

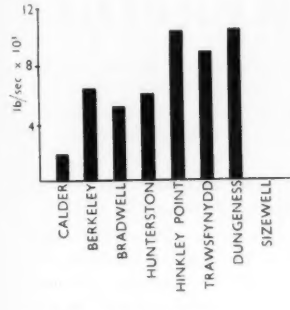


Fig. 5.—Gas flow.

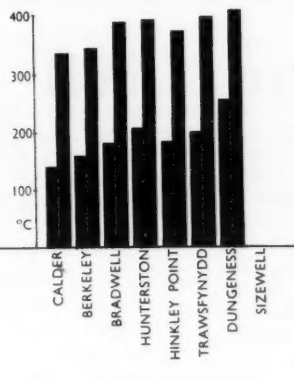


Fig. 6.—Inlet and outlet gas temperatures.

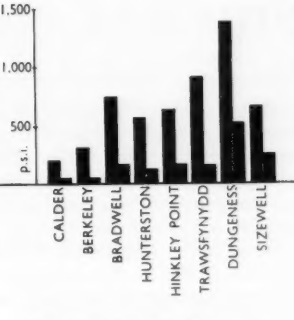


Fig. 7.—HP and LP steam pressures.

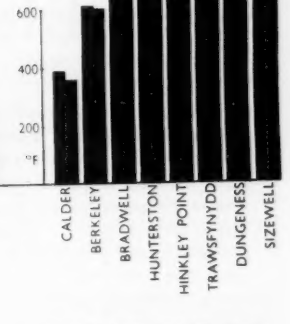


Fig. 8.—HP and LP steam temperatures.

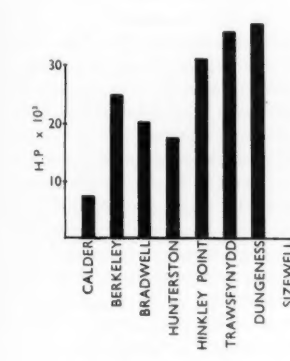


Fig. 9.—Blower power.

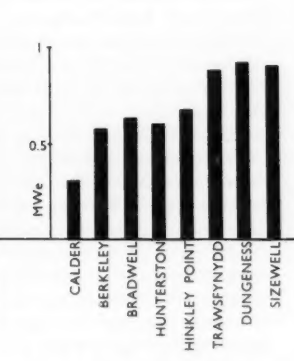


Fig. 10.—Net electrical output per tonne of uranium.

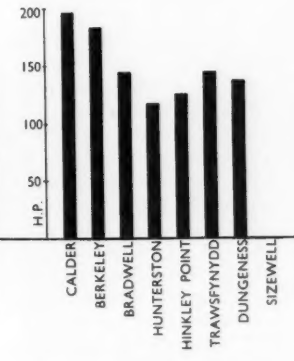


Fig. 11.—Blower power per net MW output.

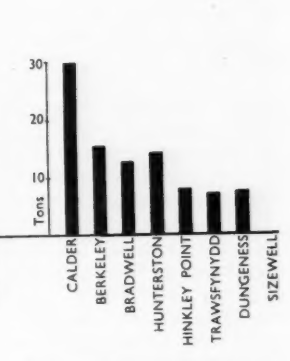


Fig. 12.—Tons of graphite per net MW output.

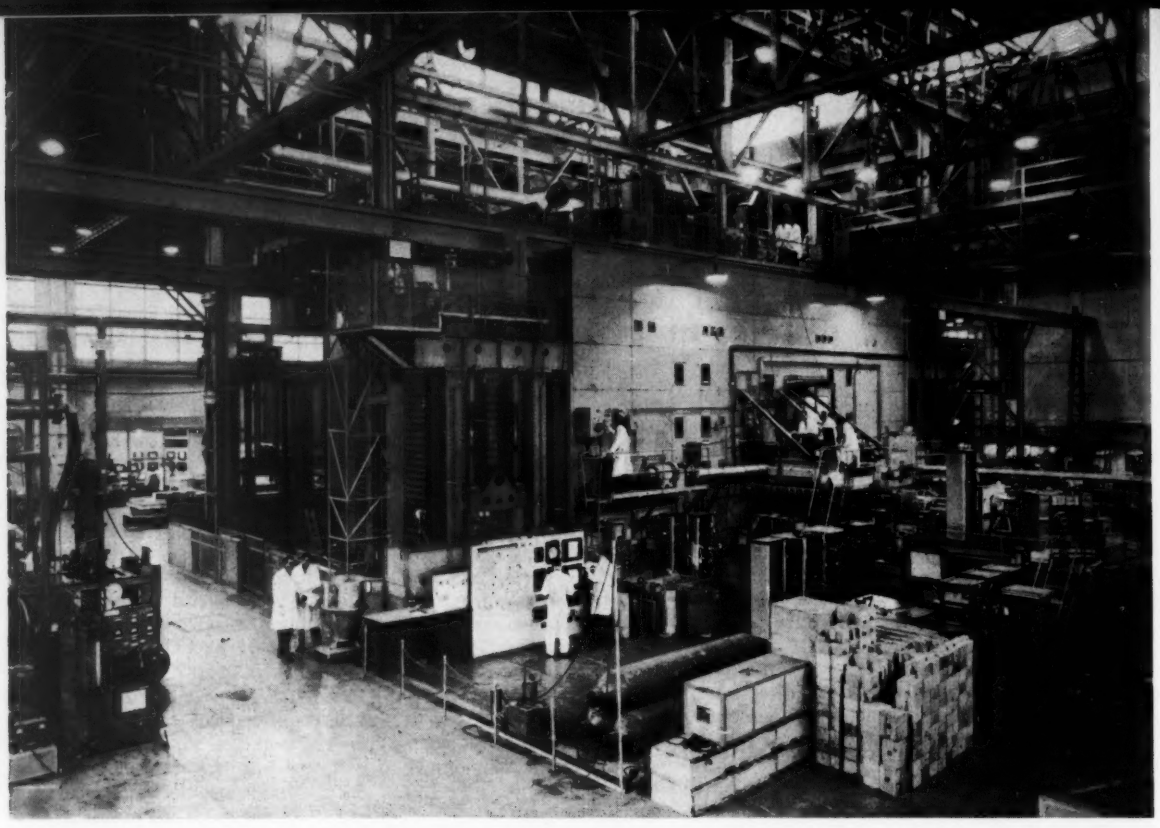


Fig. 1—Bepo, Harwell's 6-MW air cooled graphite reactor which has been such a valuable work-horse in the U.K. research programme.

Fuel Elements for Civil Reactors

The key to any civil power reactor programme is the production of fuel elements of high reliability able to withstand the burn-up required of them. With Britain's first two civil power reactors at Bradwell and Berkeley about to commence fuel loading* Nuclear Engineering *has approached Mr. L. Grainger, assistant director of AERE Harwell and former head of the metallurgy division to give his personal assessment of the status of magnesium canned metal uranium fuel element development.

by L. GRAINGER
(*Asst. Director AERE Harwell*)

THE broad results of fuel element experience in the eight reactors at Calder and Chapelcross are fairly well known although their significance and relationship to other British work are not always fully appreciated. The techniques and results of post-irradiation examination have been described by Eldred *et al*[1].

The first Calder reactor has now been on load for nearly five years. During that time fresh charges and recharges have been provided regularly and without any delay; the reactors have had an extremely high availability (one has recently run for a year at over 96%) and this has been affected only slightly by fuel element problems, in spite of the fact that operational conditions have sometimes been more onerous than allowed for in the design.

The Calder reactors are primarily plutonium producers and bulk irradiation levels are determined by operational requirements; fuel behaviour has never influenced these decisions. In addition, however, the policy almost from the beginning of operations has been to allocate some proportion of the loadings to experimental use, particularly for the higher irradiation levels and more severe conditions of the civil reactors. Some channels charged very early in Calder history for these reasons are still operating satisfactorily. Substantial numbers of fuel elements have received irradiations in the range 1 500-2 000 MWd/t (channel average) and other channels are continuing at still higher irradiations. Out of the first 70 000 elements charged, over 1 000, including all those from channels with suspected leaks, have been examined; using the most sensitive leak detection methods, faults were detected in only 25 cases. In addition, destructive examination, including metallography and the determination of mechanical and physical properties, has been carried out and has provided invaluable indications of behaviour at higher irradiations.

Taken against the original design and operational criteria, therefore, experience to date has been remarkably good in its own right. Further, although the irradiation levels so far are only about two-thirds of those intended in the civil reactors and the designs and operating conditions are somewhat different, this experience represents by far the most indicative demonstration of the expected performance and economic prospects of a civil fuel element available in the world today. It is most important also to remember that the Calder elements continue a clear line of development from the Bepo and Windscale reactors which provided important background experience. In Windscale, for

example, many experimental production-scale bars received doses up to more than 2 000 MWd/t and this early data and material were most instructive.

Out of the first 25 faulty or suspect elements in Calder, nearly half were probably due to small manufacturing defects or handling damage, in both cases generally associated with the welds (see Figs. 2 and 3 of Ref. 1); although the defective proportion was from the beginning creditably small, steps already taken may be expected to reduce the incidence to very low levels indeed. Failures due to these discrete defects are detected and removed at low irradiation levels. In about half the cases, however, failure occurred at rather higher irradiations and followed a common pattern of a clearly systematic nature; this has come to be called "cavitational failure" or "slow burst." In these cases, which were confined to the colder channel positions where the ductility of the magnesium can is at a minimum, the can wall was strained, often somewhat locally; as a result, cavities formed at grain boundaries and these could link to create minute leak paths or cracks. (See Fig. 4 of Ref. 1.) The burst fuel element detection gear detected these at an early stage; it is now known that further development of these leaks takes place very slowly and the amount of oxide formed on the bar surface is small, so that continued irradiation of such elements for considerable periods creates no particular hazard or difficulty. None the less, because of the systematic nature of the phenomenon it is most important to understand it so that its onset may be delayed to satisfactory irradiation levels for the civil reactors.

The material factors influencing the cavitational failures are the ductility of the can, under rather special constraint conditions, and the dimensional stability of the uranium bar. In addition, of course, there are very important design and operational factors, especially those associated with the magnitude, frequency, rate and distribution of strains arising from the substantial difference in the thermal expansion coefficients of magnesium and uranium.

Dimensional Changes

Overall changes in bar length have been measured for a large number of bars and were very small in most cases, with only a few per cent being greater than 0·5% and the maximum about +0·8%. Above about 500 MWd/t the changes were generally positive but at lower irradiations there were often significant small decreases in length. The bars in the coldest positions showed the greatest scatter and largest changes; in the two hottest positions practically all of the bars fell within the range −0·1 to +0·2%.

The length changes were the resultant of several processes, including volume changes, creep and irradiation growth. Up to 500 MWd/t the volume change was usually negligible or even decreased slightly; this may be due to the resolution of precipitates. By 1 000 MWd/t this densification process had saturated and the density then been reduced by about 1%, contributing 0·3% to length increases (assuming isotropy). Creep is accelerated by irradiation and a typical rate would give 0·3% compression at 1 000 MWd/t. The net changes in length may therefore be approximately due to irradiation growth. This process results from the fact that, under irradiation, individual crystals of alpha uranium increase in length in the [010] direction, decrease in the [100] direction and remain constant in the third direction. In polycrystalline aggregates, the dimensions may change or the surface may "wrinkle." The former results from some degree of preferred orientation, a preponderance of [010] directions parallel to or of [100] perpendicular to the bar axis giving a length increase; the amplitude of wrinkling depends on the grain size at or near the free surface, where the grains can grow without restraint.

The overall length changes in Calder bars due to irradiation growth cannot therefore be very large. It is known, however, that the length changes are not uniform along the bar and may be much greater locally than the average; although there is no apparent correlation between growth or wrinkling and cavitational failures, these are clearly matters for study in relation to the higher irradiations.

Whilst volume increases have been small in Calder as noted above, "swelling" is expected to be important at higher temperatures and irradiations, such as those intended in the civil reactors. This is the change in volume due to the extra atoms, especially the rare gases, formed by fission. At 0·3% burn-up (~ 3 000 MWd/t) the volume of these gases, at NTP, would be about twice that of the uranium and, if it collected into suitably sized bubbles, could greatly increase the volume. Because swelling has not been technologically important in Calder, support has been given to the view that it does not become significant below about 450°C. More recently, however, the electron microscope has shown that tiny bubbles exist even in the colder bars from Calder (Fig. 2).

Burst Development

A most desirable operational feature of any reactor system is an understanding of the mechanism of burst development in the event of a can defect, so that the faulty element can be located and removed before there could be formed any substantial amount of oxidation products which could conceivably contaminate the circuit. Gas-cooled reactors of the Calder type have always been thought to have special advantages in this respect and experience with the cavitational failures has confirmed both the general thesis and the suitability of the type of BFED normally used. However, in common with other reactor systems, it is possible to postulate circumstances where significant oxide might be formed before detection—i.e. a "concealed" burst.

In Calder, if an element with a weld defect were loaded into the hottest position, the inflow of CO_2 to react with

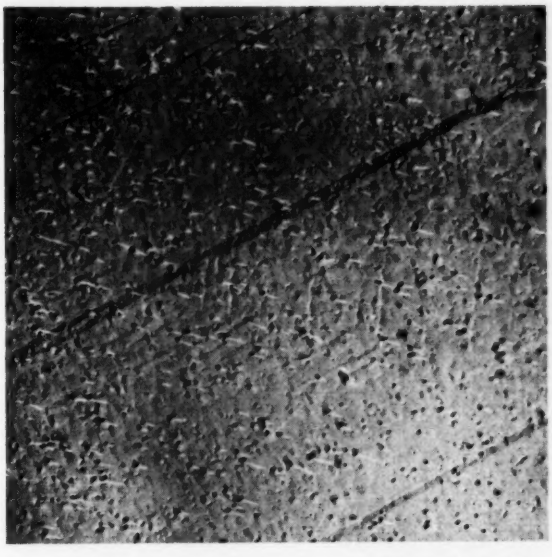


Fig. 2.—Electron micrograph of uranium irradiated at 280°C to 0·3% burn-up. Swelling about 2%.

the uranium, together with the long leak path might delay the diffusion of gases outwards; as the BFED depends on fresh fission products, the sensitivity of detection might be affected. Such an occurrence clearly depends not only on such factors as reaction kinetics but also most closely on the details of reactor design and operation; it is possible, for example, to adopt techniques which encourage fission product escape and which increase the probability of their detection. These matters are beyond the scope of the present discussion. Although there is no reason to suppose that there is any current anxiety on this score in the Calder reactors themselves, the reaction between CO_2 and uranium at the peak temperatures proceeds fairly rapidly and research devoted towards reducing the effective reaction rates could result in increased operational flexibility in the civil reactors.

Irradiation Effects on Mechanical Properties

The effect of irradiation on the mechanical properties of uranium can be important both during and after irradiation. In the reactor the uranium bars must at least support themselves, generally in the form of a stack. Late in the development of the first Calder fuel elements, Cottrell predicted on theoretical grounds that irradiation would enhance creep in uranium, as a result of the inter-granular stresses due to irradiation growth. The effect was expected to be particularly important at the lower temperatures in Calder where no creep would occur out-of-pile. Some elegant experiments with uranium springs in Bepo confirmed the effect and gave a measure of its magnitude. Careful measurements in Windscale and Calder have established the irradiation creep rates and satisfactory support devices have been introduced, but this is a factor which must always be taken quantitatively into account by designers.

Although there is ample evidence for very substantial ductility in uranium while it is in-pile, even though it may become cracked, the bars have very low or negligible ductility after removal. This has become a significant factor in handling operations, such as decanning, and at the higher civil irradiations the irradiated bars might be expected to be more cracked and brittle, although it is not thought that present handling techniques would become impracticable.

Table 1.—Swelling Results for Some Alpha Uranium Alloys

Spec. No.	Estimated surface temp., °C	% volume increase	% Burn-up (±10%)
122	380	0·95	0·13
323	424	7·4	0·28
328	424	2·9	0·21
333	424	1·0	0·13
128	493	2·6	0·18
129	493	2·4	0·18
132	480	2·3	0·18
324	476	11·6	0·36
329	476	7·9	0·28
334	476	5·6	0·18
121	514	1·3	0·13
123	514	1·2	0·09
325	538	7·0	0·47
330	538	5·4	0·36
335	538	2·9	0·23
126	627	2·3	0·43
127	627	2·7	0·43
130	618	1·8	0·43
131	618	2·5	0·45
326	584*	16·5	0·46
327	584*	Very large	0·48
331	584	3·0	0·35
332	584	6·1	0·36
336	584	1·1	0·21
337	584	1·9	0·22
118	604	4·1	0·16
120	604	2·6	0·16
217	625	4·4	0·41
191	625*	Very large	0·35

* These specimens may have been taken inadvertently to very high temperatures. Specimen numbers 327 and 191 had apparent volume increases of more than 100% but at such swellings the measurements lose their usual significance.

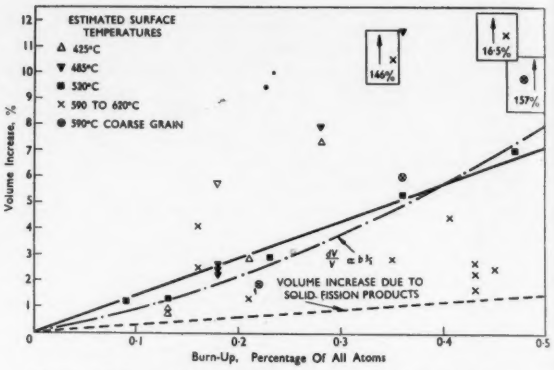


Fig. 3.—Relationship between burn-up and volume increase for a series of uranium specimens irradiated in the high alpha range.

Some Research Items

From experience to date it is clear that the main research problems relate to:

(1) Dimensional changes in uranium;
  (a) volume—i.e. swelling,
  (b) geometrical—i.e. growth (and wrinkling).
(2) Magnesium can ductility.
(3) Oxidation processes relevant to defected elements.

SWELLING

Swelling is an extremely difficult problem to study and even more difficult to understand. Experimental work has been proceeding on a considerable scale for a number of years; the initial objectives were to highlight the important parameters and, if possible, to indicate by empirical means an economic alloying addition which would significantly reduce swelling. The earlier results were difficult to categorize. Many of the unalloyed specimens (i.e. similar to Springfields civil-type fuel) showed only moderate swelling (say a few per cent at about 0·4% burn-up); other specimens, including practically all the alloyed materials except some gamma alloys, gave exaggerated swelling. The results did not appear to depend, in any completely self-consistent way, on dose or temperature. More recently the experimental rigs have been greatly improved, particularly in regard to temperature control. Also, new techniques for post-irradiation examination, both by normal metallography and electron microscopy, have been developed and have contributed greatly to the interpretation of the measurements. As a result, a much clearer picture of the phenomena has now been obtained and more definite experiments can be carried out, both to obtain data and to study mechanisms.

Some Harwell results on civil-type uranium are given in Table 1 and Fig. 3[2].

Several reservations with regard to their application to the civil reactors must be made at once. First, most of the specimens had a very poor thermal cycling history, second, the specimen containers were not intentionally pressurized; the large swellings are generally pressure sensitive and at reactor pressure would almost certainly have been several times lower. Finally, there is strong evidence that the three specimens showing excessive swelling were unintentionally taken to very high temperatures, perhaps near to the m.p., due to a breakdown of the sodium film on which heat-transfer in the rigs depends. In Fig. 3 the volume increase due to the solid fission products is shown and curves are drawn for a linear dependence of swelling on burn-up and for a $(\text{burn-up})^{3/2}$ law. It will be seen that at

these burn-ups there is little difference between these two assumptions. In fact, it is now generally recognized that the term swelling covers the volume increase due to several different processes, some of which are discontinuous or not directly related to dose and temperature.

Great attention in the research has been paid to the nucleation and growth of bubbles[3, 4]. The electron microscope has shown that in many cases bubbles of about 0·1 μm diameter are fairly regularly dispersed about 0·5 μm apart. There are theoretical reasons for believing that practically all the gas is in the bubbles and that the pressure, about 2 000 psi, is restrained by surface tension; in these cases the bubbles contribute about 4% to the swelling at about 0·4% burn-up.

A number of possible modes by which finely dispersed bubbles might grow in a regular manner have been examined. Neither creep of the matrix nor resolution of gas atoms followed by reprecipitation on larger bubbles seems possible; although vacancy capture will certainly take place its influence on bubble growth will be only slight.

When nucleation is on a sufficiently fine scale it seems that regular bubble growth processes do not normally contribute greatly to swelling; it is of particular interest therefore to consider the factors influencing nucleation. Grain boundaries and second phases are usually on too coarse a scale to influence the general nucleation, but they can exert a local influence. There is recent evidence that bubbles can be associated with dislocation networks although it is not certain yet whether this is a nucleation effect or due to subsequent processes. Small lattice discontinuities such as vacancy clusters may influence nucleation but, for practical purposes, nucleation is probably of a near homogeneous character in civil type uranium, with the fine spacing determined by basic parameters such as diffusion constants.

The importance of bubble spacing was recently shown in an analysis of various specimens, either unalloyed or gamma stabilized but all irradiated in the gamma phase[5], thus eliminating some difficulties of interpretation. In the 14 wt.% Mo alloy, nucleation was on a fine scale and swelling was very low (1% for 0·22% BU at 800°C and 2% for 0·47% BU at 700°C). In the other cases, swellings of 30-100% were experienced, with a much coarser bubble network; in some specimens, Fig. 4, creep had led to the linking-up of the bubbles near the outside of the specimen (where the irradiation was higher).

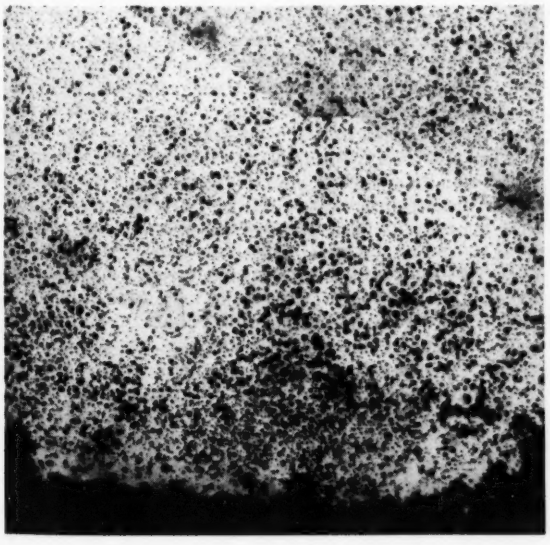


Fig. 4.—Section of U 4·3 wt.% Mo specimen irradiated to 0·48% burn-up at 700°C; 32% volume increase.

Table 2.—Swelling Results for Various Qualities of Uranium

Specimen type	Calculated Burn-up, %	Thermal history			Volume increase (from density by water displacement), %
		15 degC cycles	15–100°C cycles	100 degC cycles	
Zone melted	0·44	110	30	58	12·6
Arc melted	0·44	110	30	58	17·1
Zone melted and annealed	0·44	110	30	58	13·1
Very pure U	0·46	110	30	53	34·0
½ at.% Nb	0·46	110	30	53	24·2
½ at.% Ti	0·46	110	30	53	20·2
Ultra pure U ..	0·65	110	30	53	Breakaway
Gamma quenched ..	0·65	110	30	53	15·3
Very slow cooled ..	0·65	110	30	53	Breakaway
Civil type	0·70	3 184	18	64	9·6
½ at.% Ti	0·70	3 184	18	64	30·8
½ at.% Nb	0·70	3 184	18	64	27·0

It is not known why practically all the low alloy specimens have shown large swellings and some of the earlier results must now be regarded with reservation. However, it is likely that the important factor in many cases has been a coarse nucleation spacing; there is no explanation of how alloying should influence this but it may perhaps be through the diffusion constants or the dislocation spacing. What seems clear is that civil uranium, which contains small quantities of a number of elements, both impurities and deliberate additions, has the favourable spacing given above and that the volume increase due to actual gas bubbles is only a few per cent, up to about 0·5% burn-up at least. There is some recent evidence (Table 2) that fairly small departures from the normal composition and micro-structure greatly increase the swelling, probably by coarsening the bubble spacing. The excellent result for the civil type specimen in Table 2 is very noteworthy, especially in view of the thermal cycling history.

In the specimens recorded in Table 1, about one-third of the specimens had grain boundary cracks which contributed about 1% to the volume increase and those irradiated below 500°C had ragged holes, large in comparison to the bubbles, which accounted for about 5% swelling. These departures from the regular bubble pattern are undoubtedly of the greatest practical importance and various possible mechanisms have been suggested. Theories are mainly of two types: mechanical cracking at existing boundaries and the sweeping up of bubbles by the movement of grain boundaries. The grain boundary movement might be due to recrystallization or grain growth or to applied stress; the distribution of other phases may play a part in this. Although some evidence shows that this grain boundary process can operate, at least in post-irradiation heating experiments (Fig. 5), it is not generally thought to be so important as mechanical cracking. The latter, below 500°C, is thought to be due to growth stresses and the appearance of the holes certainly supports this. At higher temperatures thermal cycling stresses are probably responsible; in the high alpha range a cycle of only about 5-10 degC may perhaps be adequate to form a crack at a boundary but just above 500°C, cycles of $\pm$25-50 degC may be necessary. It is important to distinguish between and

Fig. 5.—Electron-micrograph of uranium as Fig. 2 but heated for 1 hour at 730°C. The bubbles are marked by white tails or shadows.

evaluate these mechanisms since they indicate the ways in which improvements may be sought. For example, if mechanical cracking is important, factors which increase the grain boundary rupture strength (or reduce stresses for relieving plastic flow) may be helpful. It may be difficult to control the absolute irradiation growth rate but its grain boundary effects might be modified, possibly through the grain size. Recrystallization and boundary movements may also be influenced by grain size and by composition, especially dispersed phases. All the mechanisms seem likely to be made worse by thermal cycling; close control of this and of grain size and grain boundary properties seems essential.

The above picture seems broadly satisfactory for swellings up to about 10%, or perhaps 15%. Different explanations are necessary for larger values, especially the very large or " breakaway " swelling. In some cases, with alloyed materials, this was probably due to coarse bubble nucleation, followed by growth by creep. In some other cases, the results are probably invalid because of runaway temperatures. It is not easy to see how a typically good specimen with favourable bubble distribution can enter the breakaway phase. Bubble interaction is not likely to become important until about 25% volume increase has been experienced, corresponding perhaps to 1·0-1·5% burn-up. Cracks and holes might collect gas from the surrounding areas and open out under pressure; it is clear, however, that only a thin shell can contribute once the crack has formed, since fine bubble arrays are observed quite near to cracks. It might be thought that a moving boundary, sweeping through a gas-filled area might be more dangerous; it is not easy, though, to imagine it moving once enough bubbles had been collected to form a continuous crack. Another suggestion is that in a badly cracked specimen the thermal conductivity might be reduced so that its temperature rises substantially but the cracking of the specimens seen to date hardly seems to be on a sufficiently fine and extensive scale for this.

It seems quite likely, therefore, that breakaway swelling, in civil type uranium, may be spurious or, if possible, may require exceptional conditions, such as thermal cycling of a severity much greater than that applicable to power reactors. Calder experience, though limited, tends to support this.

From the above, it will be clear that the experimental difficulties in studying swellings are very great, in view of the fact that one specimen can only give one point on a multi-dimensional curve. This has led to a revision of the experimental programmes into the following types:—

(a) Qualitative exploratory experiments and studies of basic mechanisms.

(b) MTR experiments on small specimens to give " spot " data closely related to civil reactor conditions and composition.

(c) Full size replica experiments in Calder type reactors, again closely reproducing the correct conditions.

GROWTH

Growth is the principal phenomenon which determines the stability of the uranium bars, both dimensional and surface, at the lower temperatures in the reactors; whilst it is now known that growth continues at temperatures above 400°C, it is of most concern (apart from its influence on swelling) in the region of 200°-300°C where it is most rapid and magnesium ductility is least. Broadly, a fine grain should obviate swelling and a truly random crystal orientation yield no overall geometric changes. The research aspects of these problems are:—

(a) Mechanisms and absolute growth rates of single crystals.

(b) Interactions between different crystals and between different portions of bars.

(c) Measurement of preferred orientation.

(d) Origins of orientation—i.e. phase transformation.

(e) Alternative alloys and heat-treatments.

It has frequently been thought that growth rates had a maximum at about 200°C. Recent work at Harwell (Table 3) shows conclusively that this is not the case, rates at 77°K being an order of magnitude greater than at 350°K (the growth rate, $G \propto$ (fractional extension)/(burn-up)). The G-values decrease linearly with increasing temperature, reaching zero between 450 and 500°C; at the lowest civil reactor temperatures the unrestrained crystal growth would be 100% or more at doses of interest. These recent Harwell observations are very important additions to the experimental data which a satisfactory theory must explain but, although the literature on this subject is voluminous, there is as yet no commonly accepted mechanism. It seems fairly certain, however, that little can be done to influence fundamental growth rates of alpha uranium and that practical measures depend on integral restraint. Measurements on Windscale bars showed that wrinkling was worst at about 150-200°C and this was thought to confirm a growth rate maximum at these temperatures; now that the latter is known to be untrue, different explanations, related to the temperature dependence of accommodation by grain boundary flow, slip and twinning seem more possible. Work has also been carried out to measure accurately the growth of thin " pencils " cut axially from rods at different radii and along the length of full size bars, to throw light on the effect of macro-stress relief on bar dimensional changes. These measurements frequently show small but significant differences between core and rim portions, which are consistent along the length. This difference is in the sense that could explain the slight dishing of the end which is often observed, as it can be assumed that the core and rim mutually restrain each other except at the ends.

This precise method of irradiation growth measurements on pencils is perhaps the most sensitive way of studying preferred orientation, although it has the disadvantages of being both destructive and very time-consuming. Many

Table 3.—Growth Rates (G) of Alpha Uranium Irradiated at 77°K and 350°K

Specimen	G at 350°K	G at 77°K
Polycrystals, material (A)	980	11 000
	990	10 200
	1 040	9 980
material (B)	740	7 700
	745	7 600
	745	7 750
Single crystal 1	420	3 900
Single crystal 2	770	8 000

Thermal neutron fluxes are $\sim 1{\cdot}3\times10^{13}$, and burn-ups are up to $2{\cdot}6\times10^{-4}$.

other methods have been examined but the difficulty and complexity of such determinations are very great. As an illustration, the most extreme bar dimensional changes observed in Calder could be explained if, out of each group of 100 crystals, one or two were aligned in a particular direction, the rest being completely random; further, recent work suggests that this slight orientation changes continuously from the core to the rim, the distances being such, compared with the grain size, that randomness becomes difficult to define.

The absorbing power of uranium for X-rays is such that too few grains are penetrated for statistically meaningful results. Neutrons have much greater penetration and diffraction measurements in Dido have recently provided confirmation of the general orientation distribution suggested by the growth measurements. Unfortunately, this method has its own disadvantages, especially the low effective neutron beam intensities available, and it has been necessary to use fairly large specimens, laboriously assembled as mosaics of small pieces cut from the appropriate portions of bars, and to count for very long periods. Other methods which have been studied are all based on the anisotropy of alpha uranium and include ultrasonics, thermal expansion and thermal cycling. At Harwell, ultrasonic wave velocity has been used to distinguish slight differences between different parts of bars and although there is an ambiguity in interpreting the results in terms of grain orientation, they are not inconsistent with the picture obtained by other means. In addition, ultrasonic wave attenuation, which has long been known to be related to grain size, has been developed into a much more sensitive method which is now suitable for production control; areas of large grain size, or associated grains, which sometimes remain after heat-treatment and may contribute significantly to irradiation effects, may be detected by this means and the bars recycled.

It is often suggested that the Springfields traverse quenching method inherently gives rise to some preferred orientation but theories on these lines are not completely satisfying in detail; in any case, if this were so it might be expected that the degree of orientation would be much greater than it is. It is possible that any beta quenching method will result in orientation because of the radial heat flow and stress patterns. Information on this will be given by basic beta-alpha transformation studies, including the effect of applied stress and gradient quenching on orientation.

If the research shows that orientation is inherent in bars produced by the usual route and the full scale irradiation trials indicate that it is technically important, it may be necessary to consider completely different methods of obtaining a random fine grain. Of particular interest are the molybdenum alloys in the range 1-5%, which offer the possibilities of isothermal transformation, direct conversion from gamma phases or fine grained as-cast structures. These alloys are scientifically very interesting and complicated and workers in France have made outstanding contributions to the physical metallurgical research. It must be emphasized, however, that full-scale experience with molybdenum alloys is very small compared with that on civil type fuel.

MAGNESIUM CAN DUCTILITY

Although emphasis in research on magnesium has been on ductility, especially at the lower temperatures, it is most important to bear in mind that many other factors must be taken into account, including formability, compatibility, weldability, neutron absorption and creep strength. It must also be appreciated that magnesium in cans, compared with normal engineering usage, is employed over an exceptionally wide temperature range (in relation to m.p.) and is taken to unusually high plastic strains. It is also relevant that the series of Magnox alloys originally studied at Harwell, and from which the present A12 material was derived, was initially intended for air-cooling and this resulted in strong emphasis on oxidation resistance. Considering this background, a current reappraisal might tend towards dividing the problems into different temperature areas, with some relaxation on air oxidation resistance.

A12

Since the early exploratory studies, much of the work has been carried out elsewhere than Harwell, especially at Culcheth and in the consortia's laboratories. A most important part of this work has been the study of the ductility of magnesium alloys as a function of temperature and strain rate, and of material factors such as composition and grain size; a key aspect of this work has been a comprehensive study of mechanisms leading to cavitation and fracture. It was found at an early stage that the behaviour of A12 was complex: while ductility increased generally with temperature and strain rate, there could be a minimum in the region of 200-275°C; there were some indications also of a strain rate minimum. The metallographic evidence confirms the general picture of several competing processes with different temperature and strain rate dependence. Below about 200°C deformation is accompanied by the formation of angular fissures; above this, the transition temperatures depending on grain size and strain rate, the fissures are gradually replaced by round cavities at the grain boundaries. The intensity of cavitation,

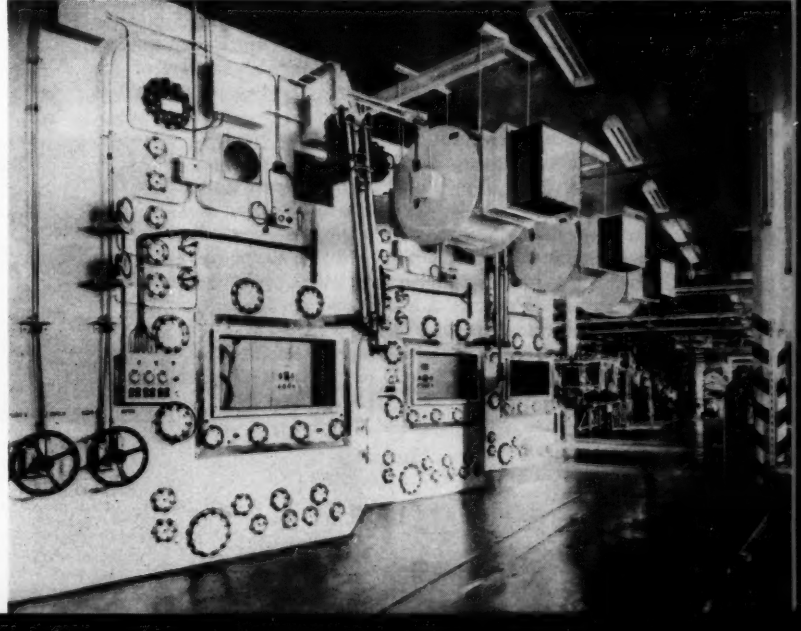


Fig. 6.—Three high activity caves which have recently been brought into commission at AERE for metallographic work.

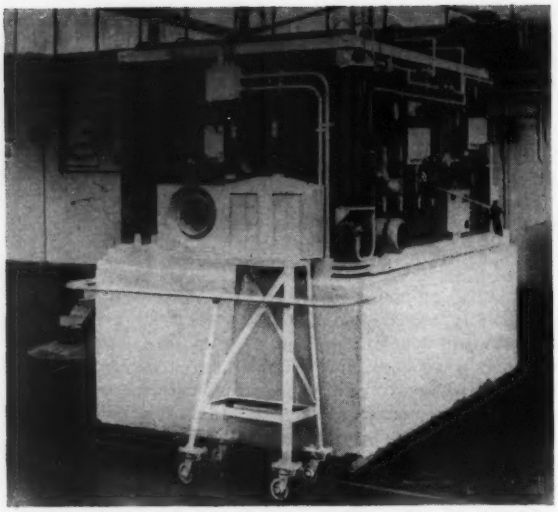


Fig. 7.—A free standing lead shielded cell for specimen preparation or testing.

and its general distribution, increases with temperature up to the minimum in the ductility curve and thereafter decreases; link-up of cavities may be an important part of the fracture mechanism near the ductility minimum. Cavitation is less severe in fine-grained materials. A number of theories have been advanced to explain cavitation but none is completely acceptable. A broad picture which fits most of the facts depends on grain boundary sliding; if slip occurs in one grain before the other, dislocations can pile up, forming a cavity as sliding continues. At low temperatures and rapid strain rates, grain boundary sliding will not take place so readily; at high temperatures and slow strain rates, grain boundary migration will eliminate the source of cavities before they are formed.

Particular attention has been paid to grain size effects in A12. In one series of creep tests at 200°C, for example, the strain at fracture increased from less than 10% to over 50% as the grain size was reduced from about 0·040 in to 0·002 in. The application of creep ductility data to fuel element analysis is complex; if failure coincides with the first linking up of cavities, a higher proportion of the fracture elongation may be available in the case of the fine grained material. Another complication is that in a creep test the load is constant, so that the first neck to form takes most of the subsequent strain, the local ductility being much higher than the normally measured elongation. In the conditions of strain applicable in a can, it is possible that these high local deformations are more relevant and complex strain tests suggest that the advantages of the fine-grained material are even greater when judged by this criterion.

Grain size control is therefore of the greatest importance, but although this is readily achieved by strain anneal methods in test pieces, cans are subject to fabrication strains and heating at several different stages in their history and subsequent service. Close control of all manufacturing stages followed by the optimum annealing is desirable but needs considerable development. For the first civil elements it has been forecast that grain refinement equivalent to an improvement in ductility by a factor of three should be achieved, compared with standard Calder elements; further improvements seem possible.

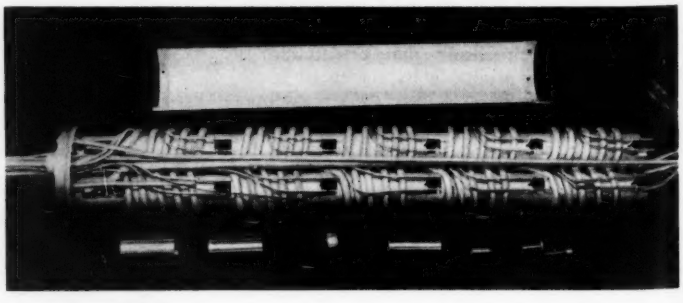


Fig. 8.—Example of an in-pile test assembly for irradiating specimens.

ZA

The ZA alloy (0·6% Zr) is naturally fine grained (about 0·001 in) and is the standard French alloy; more recently it has been studied here on an expanding scale. In creep tests its ductility at low temperatures is higher than even the finest grained Magnox: at 200°C, 75% compared with 50% for fine grained A12, under one particular set of conditions. Although the French have given broadly favourable reports of ZA, its physical metallurgy has some complications about which little is known. It is possible that ZA is not fully stable in a metallurgical sense, so that precipitation might occur, possibly assisted by irradiation, on prolonged service at the highest civil reactor temperatures.

It is probable that grain size stability in ZA depends on a second phase at the boundaries; in other metals depending on such an effect there are cases where the stabilization breaks down anomalously, with very rapid local grain growth. It is also known that ZA can readily pick up hydrogen with subsequent precipitation of zirconium hydride; both these points have been reported on briefly by the French[6]. Very good grain stability was shown at 450°C and it was suggested that hydride precipitation was beneficial both to this and to the mechanical behaviour. Much more basic data would be desirable, however, including the effects of irradiation, temperature excursions and other possible reactor variables, in support of full-scale prototype manufacturing and irradiation trials. It is also not certain that the present composition is the optimum, and some research on the zirconium level and other constituents is indicated. It is also necessary to carry out tests to establish that ZA has adequate creep strength at the highest temperatures, a point on which no alloy is likely to have any considerable margin, and to study its oxidation under reactor fault conditions. It will be noted that the doubts about ZA relate almost entirely to its service in the hot positions, where its presumed advantages are least important.

Irradiation Studies

At Harwell, most emphasis has been on the assessment of possible mechanisms of irradiation damage. It has been established that the normal process of hardening, by defect creation, can have little significant effect at reactor temperatures. A theoretical study of nuclear reactions giving rise to gases has shown that the quantities are negligible unless a very high degree of concentration could be brought about, perhaps by extensive grain boundary movement which is in any case undesirable. Damage by fission fragments from the uranium has also been studied but

seems unlikely to be important. In view of the importance of small variations in magnesium ductility, however, and the large programme of out-of-pile work, further irradiation experiments are in hand; these use the growth of uranium, in which a small degree of orientation has been induced, in order to strain idealized cans.

Oxidation Processes Relevant to Defected Elements

Research in this field falls into two categories: determination of basic reaction rates and mechanisms, and the study of possible protective measures.

Reaction rates have been determined for the U/CO_2 reaction at temperatures up to 1 000°C. At 400°C, a rate of 0·1 mg/cm²h was found, increasing rapidly at higher temperatures; at 500°C the rate was 1·4 mg/cm²h and the rate of increase was greater at the beta/gamma change point. Self heating could be obtained at 700°C and above, depending on the heat-transfer conditions. The reaction rates are generally linear with time and the rate controlling step is thought to be the diffusion of oxygen ions through the oxide film. Water vapour does not accelerate oxidation under conditions of practical interest.

There are, however, special circumstances in the case of a fuel element with restricted free space and a small defect, and which is generating heat. Oxidation may not proceed uniformly and the insulating properties of the oxide will tend to increase the temperature locally at the oxide/metal interface at the points where reaction is taking place. However, reaction probably takes place in two stages, to CO and then to C; the second stage may be considerably slower so that the build-up of an oxide mound, in a semi-stagnant system, may depend on the rate at which the CO can be mopped-up over the bar surface generally. Therefore, for a full kinetic understanding of oxidation in defected elements, one needs to know the rates for the different reactions over a wide range of temperatures and the effects of irradiation on these processes.

Protective measures may be of several types:

(a) General alloying.

(b) Coatings.

(c) An extension of (b), bonding of the bar to the can, thus limiting the access of gas to the uranium.

A wide range of alloying conditions was studied at Harwell some years ago and it was concluded that the improvements which could be obtained with moderate additions were not worthwhile. More recently, however, the effects of uranium purity have been studied and it has been shown that high purity uranium is much more resistant to CO_2; certain impurities normally present appear to destroy the initially protective nature of the film. Whether it would be possible and/or advantageous to modify the base composition of civil fuel remains to be seen; it would in any case have wide repercussions.

One interesting speculative way in which the oxidation resistance of pure uranium might be exploited would be to deposit a thin layer on to normal quality bars. For coatings of other metals, particular attention has recently been paid to vapour-phase deposition, with oxide removal from the uranium taking place concurrently through a volatile halide; some initial success has been obtained with copper, aluminium, zinc and magnesium. It should be appreciated, of course, that if the mopping-up of CO by the bar surface generally is important in burst development, then even quite permeable or imperfect coatings may have considerable value.

The bonding of uranium to magnesium presents formidable difficulties, especially as the metallurgical structure of both can and bar need such close control. Of possible interlayers, zirconium seems least unlikely.

PROSPECTS FOR MAGNESIUM/URANIUM FUEL ELEMENTS

The manufacture of the fuel elements for the first charges of Bradwell and Berkeley is currently in hand; before significant results are available from these elements, manufacture of first charges for several other stations will be committed. It is appropriate therefore to consider first the possible fate of these initial charges and then the improvements, short and long term, which might be introduced later. Although the highly developed heat transfer processes of the civil reactors give rise to possible severe stressing of the fuel elements, this will not here be taken into account; it will be assumed that these matters can be dealt with without reflection on the more truly metallurgical aspects.

It will also be assumed that the control of burst development will be primarily an operational matter, not influencing fuel element life; this is a reasonable assumption in view of the number of reactor years of experience on the Calder and Chapelcross reactors. The research on oxidation processes should assist the operators to improve this control continuously. If modifications to materials in order to reduce the rate of burst development should seem worth while, it is possible that an adequate improvement could be obtained by modest changes in the impurity specification, or perhaps by a thin coating of high purity uranium. The prospects for the development of suitable coatings of other metals, at least to provide some further protection, seem reasonable but they might not justify their extra cost. Bonding of can to bar would be very difficult but one or two ideas are worth a little speculative research.

It can also be taken for granted that the fuel elements will be manufactured to a very high standard and this will reflect back favourably on the consideration of burst mechanisms.

On these assumptions, and since it seems somewhat improbable that any serious new phenomenon, so far unobserved in Calder, will prove to be of great importance, estimates of life depend mainly on the consideration of cavitation failures and swelling. It can be said quite confidently that wholesale failures from these causes are most unlikely to occur at irradiation levels well below the current objective of 3 000 MWd/t (average). Whether the full target will be achieved immediately depends on extrapolations which are sufficiently difficult as to make precise predictions, in advance of experience, somewhat unwise.

Cavitation Control

If no improvements, compared with Calder, were being introduced into the civil elements, the first limitation would probably arise from cavitational failures, although it is not known to what extent this may be tolerated. However, the civil elements incorporate a number of improvements, notably in fuel element design and in can ductility. A factor of three improvement in the latter has been forecast[7] and it also seems likely that the effective ductility will be more favourable than that measured in standard creep tests. On design aspects, the strains may be more favourably distributed, because of better anti-ratcheting arrays and the longitudinal fins; the higher reactor temperatures may not eliminate the ductility minimum but may reduce the channel length involved. Although no formal substantial changes in bar structures have been introduced, growing experience in manufacture may be expected to result in gradual improvements, perhaps including a more consistently fine grain size; the ultrasonic inspection technique should assist in this. If, for example, grain size control is relevant to bar stability, as seems very

possible, and the poorest 10% of bars in this respect were eliminated, the effects might be very advantageous.

Bar distortions seem inadequate in themselves to provide all the strain contribution to cavitation; some portion, perhaps even the majority of the strain, may result from differential thermal expansion effects. In this case, in addition to the improved design aspects, the small extent of thermal cycling in the civil reactors could provide a most important factor of advantage.

Taking all these factors into account, cavitational failures may not limit even the first charges below 3 000 MWd/t. For further improvements, first emphasis will probably be on the can; although substantial advances may be expected with A12, it seems quite likely that a change may be made to a Mg-Zr alloy for the colder positions, after thorough proving under U.K. conditions to high burn-ups.

The directions in which enhanced bar stability may be sought will depend to a considerable extent on the results of some of the current research. It seems quite possible that a better understanding of orientation and growth processes may well lead to refinements of the present techniques to the point where bar distortions will have a negligible effect on cavitation failure rates. If this is not adequate, more fundamental changes to the heat-treatment of existing civil type uranium or the introduction of a low molybdenum alloy may have to be considered; research on these alternatives is well advanced. It should be noted, however, that molybdenum alloying involves economic penalties which need to be very carefully set against the presumed advantages. Although the French have chosen an alloy of this type for their gas-cooled reactors and have reported excellent stability in their test reactor, EL3, up to 7 000 MWd/t, there is no information of the detailed statistical type published for Calder; it may be observed from the latter that a very large proportion of the bars are very stable and it is only the most critical examination which indicates where improvement might be desirable.

It will be seen therefore that there are several clear and promising lines of material development with regard to the cavitational failure problem; not all need be successful to take the life expectation beyond 3 000 MWd/t. In addition, there are design and reactor operating factors, especially with regard to thermal cycling, which could be important.

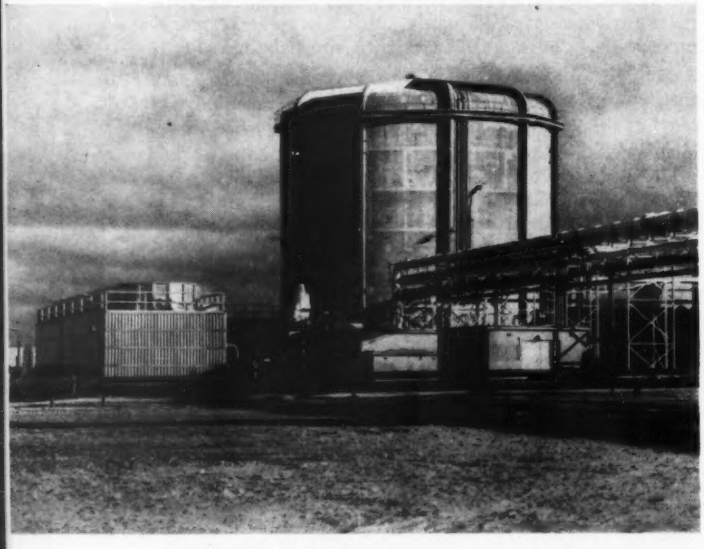


Fig. 9.—The 10-MW materials testing reactor at Dounreay.

Swelling Control

It seems more difficult not only to assess swelling but to devise means of limiting its extent and effects. The hottest civil elements will need to be taken to about 4 500 MWd/t to achieve an average burn-up of 3 000 MWd/t. At these levels, MTR specimens of civil type fuel have generally behaved reasonably well; when thermal cycling has not been too pronounced, the results have been excellent. However, with small specimens of civil type fuel there have been a few cases of fairly advanced swelling at moderate burn-ups and one or two instances of exaggerated swelling; such behaviour has also been observed, more frequently, with other types of material. A full understanding of these occurrences is clearly desirable.

Some of the poor swelling results may be spurious and tentative explanations for the effects of composition or structure are becoming available. In addition to rig problems, however, it seems possible that MTR specimens tend intrinsically to give a higher swelling than would be obtained on full-scale bars under nominally similar conditions of temperature and burn-up. Support for this comes from the Calder experience since it is now known that bubbles are present in most, if not all, the material and also that the hottest Calder fuel comes well into the range where MTR results are not very sensitive to temperature (450°C may even be worse than 550°C). There are several possible reasons why the MTR results might overstate swelling: specimen size effects; different microstructures resulting from small-scale preparation of the enriched specimens; steeper thermal gradients and more rapid movement of gradients in thermal cycling; lower external pressure. The MTR experiments will of course continue to be valuable with regard to mechanisms and as an indication of magnitude, but measurements on full-scale bars irradiated under conditions closely resembling their correct environment will probably prove to be essential for the assembly of data; experiments presently in the Calder reactors may well settle this point.

The best possible forecast is that swelling is likely to be just about acceptable in the earliest charges, but the degree of uncertainty on the basic data is quite substantial. For improvements in the future, the first emphasis may be on obtaining a clearer indication of the rôle of thermal cycling, both qualitative and quantitative as this is one way in which the results might be affected on existing designs. Secondly, it should be possible soon to establish more definitely the influence of grain size, composition and distribution of impurity or alloying elements; if by this means the best MTR results can be reproduced consistently, as seems not unreasonable, the situation would be most satisfactory. Initially this would involve relatively minor adjustments to current civil fuel.

The prospects for alloying as a means of preventing swelling seem doubtful. The gamma molybdenum alloy would almost certainly give excellent results but even though smaller additions are necessary to stabilize gamma under irradiation than out-of-pile, the quantities are still such as to impose severe economic and operational difficulties. Harwell work has not so far shown any advantage from the alloys in the range 1-5% Mo, although there are suggestions on these lines from French and American workers; it is not certain that these results are really relevant to swelling but more conclusive tests are in hand.

Summing up the life prospects, it seems most likely that the figure of 3 000 MWd/t will be achieved, at least within the first few years of operation. Furthermore, as the fundamental phenomena are becoming more fully understood and seem susceptible to some measure of control, there is scope for further improvement; in view of the

intensive nature of the irradiation effects, however, especially swelling, it would be unwise to take, as a guide to research, a target of more than, say, a 50% extension in life beyond 3 000 MWd/t.

Operation and Design

Even at 3 000 MWd/t, the comparatively low fuel replacement component of power costs, taking a nominal figure of £20,000/t for fuel elements, is one of the attractions of nuclear power; the economic effects of extended life are quite complicated but, although obviously less than pro rata, could be quite significant. Other factors, such as primary ore costs, could combine over the next decade or so to reduce effective fuel replacement costs considerably further. It is beyond the scope of this paper to discuss these points except to emphasize that a reliable magnesium/uranium fuel element, capable of achieving an average irradiation of 3 000 MWd/t or more, is likely to have great economic attractions, which could strongly influence decisions on reactor utilization and lifetimes, and thus reflect back on other components of nuclear power cost.

Consideration has also been given to the possibility of changes in the design or operational conditions, especially with regard to maximum temperatures and shuffling procedures. The maximum temperature is influenced by a number of criteria, of which one of the most important is that the centre of the fuel should not enter the beta phase (with a given system of probabilities), as it is thought that a phase boundary, moving under the influence of power fluctuations, would be very effective in promoting swelling. This would be most difficult to demonstrate, especially with regard to the effects of a few minor excursions at various stages in the lifetime; part of the work would need to be done on actual fuel elements in a power reactor and would be expensive and time-consuming. Gamma phase molybdenum alloys might allow the temperatures to go up to 700-800°C (but this would involve drastic redesign). Apart from some narrowing down of temperature allowances and deviations, it would seem better to accept the present limits and to rely on new concepts such as the AGR for substantial temperature increases.

Fig. 11.—Group of lead shielded cells for handling irradiated specimens

Axial shuffling has considerable attractions on paper, especially in the initial working up of the reactors. It should be clear, however, from the discussion above that there are strong tendencies to develop elements with rather different characteristics for the hot and cold positions; also, metallurgical changes occurring in hot elements would be expected to reduce their suitability for subsequent irradiation in cold positions and vice versa. Therefore, although further study is obviously warranted, it would be unwise to be optimistic about shuffling.

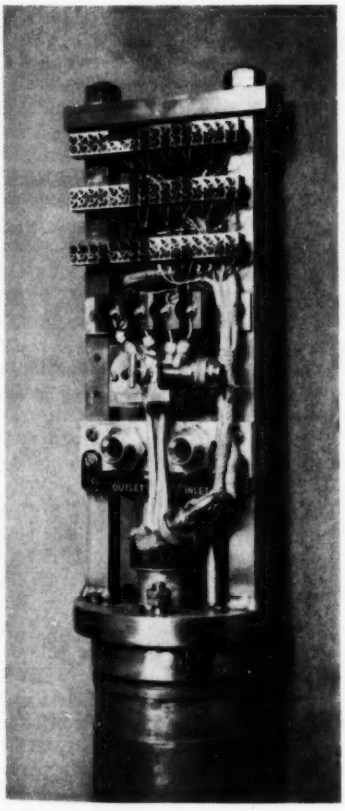


Fig. 10. — View of typical out-of-pile connections to an in-pile experiment.

Conclusions

The overall prospects are favourable for the magnesium/uranium fuel elements derived from the Calder type for civil use. The elements are expected to have a very high degree of reliability as manufactured. Some possible failure mechanisms are seen and these might influence the behaviour of the first charges at irradiations approaching the 3 000 MWd/t level, but should not be unduly troublesome at substantially lower exposures. Research has contributed substantially to the understanding of these limiting factors and has indicated ways in which the life of the elements might be further extended. Operational procedures in the reactors, especially thermal cycling, are expected to have most important consequences. Important advances in maximum fuel temperatures are unlikely, however, and the possibility of shuffling needs to be considered with caution.

ACKNOWLEDGEMENTS

I should like to thank Mr. J. W. B. Cunningham, deputy managing director, Production Group, for valuable discussions and for permission to publish some of the information in this article.

I should also like to pay tribute to Dr. H. M. Finniston, formerly head of Metallurgy Division, AERE, but now of C. A. Parsons, Ltd., under whose guidance much of the relevant research was initiated.

Dr. G. W. Greenwood, who has taken a leading part in the swelling work, was formerly on the AERE staff but is now with the CEGB; some of his research was carried out while on attachment to AERE from the CEGB.

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Brittle Fracture and Reactor Pressure Circuits

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A review of the conditions under which brittle fracture could occur in a reactor pressure circuit; methods of testing the brittleness of steel and the effects of neutron irradiation.

THE integrity of a large welded steel structure is the outcome of well-known design procedures based on tensile strength and creep strength, and these ensure that the vessel will not fail by excessive creep or yield, under the prescribed conditions of service. There remains, however, another mode of failure which so far remains a possibility, namely, brittle fracture.

The existence of brittle cracking as a mode of failure of a steel plate or beam has only been understood as such over the past 20 years, though there are many recorded instances of failed bridges, tanks, etc., over the past 75 years which seem to be examples of brittle failure. Shank[1], for example, has reviewed the available information on a variety of past cases of sudden failure and has found that these fit in well with our present views on the subject. More recent interest in the phenomenon started during the war mainly as a result of the many, and in some cases spectacular, failures among the all-welded tankers constructed over that period. These failures consisted of cracks from a few inches to many feet in length, some indeed travelling right round the hull and severing the ship completely.

Nearly all occurred almost instantaneously, and had a typical crystalline appearance. These features are now accepted as characteristic of the phenomenon of brittle cracking as opposed to the more slowly moving, fibrous-looking ductile fracture. A further difference is that a brittle crack can travel through a plate under a stress considerably lower than its yield stress, little or no necking being observed and relatively little energy being absorbed in the crack compared with a ductile or tough fracture. Examples of the two types are shown in Fig. 1. A fortunate feature of a fracture surface is that it often shows a herring-bone pattern which indicates the direction of propagation,

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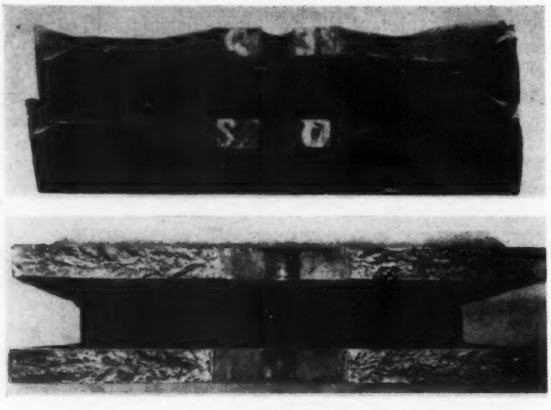


Fig 1.—Steel plates showing (top) typical ductile fracture with smooth, inclined fracture surfaces; (below) a typical brittle fracture with chevrons pointed toward the source of fracture.
(Parker, "Brittle Behaviour of Engineering Structures," John Wiley, 1957.)

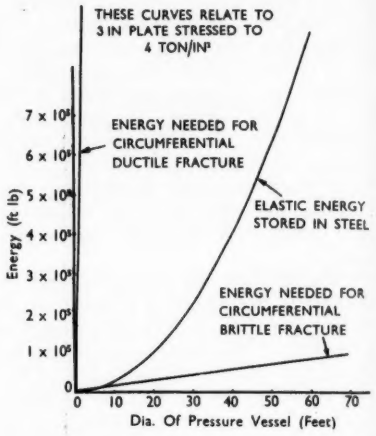

THESE CURVES RELATE TO 3 IN PLATE STRESSED TO 4 TON/IN²
ENERGY NEEDED FOR CIRCUMFERENTIAL DUCTILE FRACTURE
ELASTIC ENERGY STORED IN STEEL
ENERGY NEEDED FOR CIRCUMFERENTIAL BRITTLE FRACTURE
Energy (ft lb)
7 x 10⁸
6 x 10⁸
5 x 10⁸
4 x 10⁸
3 x 10⁸
2 x 10⁸
1 x 10⁸
0
0 10 20 30 40 50 60 70
Dia. Of Pressure Vessel (Feet)

Fig. 2.—The stored and fracture energies of a spherical pressure vessel.

and so allows the initiating point to be located. It is now fully recognized that brittle cracking is only possible below some critical or transition temperature. This temperature is not easy to define precisely and varies with type of steel, fabrication history and mode of service.

Mechanics of Brittle Cracking

There are two distinct stages in a brittle failure—the initiation of a crack and its subsequent propagation. The necessary conditions for the propagation of a crack are that the material should be below a certain transition temperature and that there should be an adequate supply of elastic strain energy available. A brittle crack requires about 2-10 ft lb/in² of fracture surface, this energy being in part the cohesive energy of the newly created surfaces but mainly the plastic work done in microscopic tearing and in creating the so-called "shear-lip" at the edge of the plate. The energy a crack needs for its continued propagation must be readily available as elastic energy. The energy of a gas pressurized in a pressure vessel, for example, can play no part in assisting the propagation of a crack. In small structures there may not be adequate elastic energy for such cracking, but as the dimensions of a given structure increase, the stored energy soon exceeds the necessary amount, thus making failure possible. This may be illustrated by the case of a spherical pressure vessel. If such a vessel is constructed from 3-in plate and is to be operated at a hoop stress of 4 ton/in² then the total elastic energy stored in the plate varies with the square of the diameter of the vessel as shown in Fig. 2. The energies required for a complete equatorial fracture are also shown for both brittle and tough behaviour. Owing to the finite velocity of elastic waves, all of the energy in the sphere will not be available to a fracture, but it is clear nevertheless that ample energy for fracture is available, particularly in large spheres. It is worth adding that in this example the ductile fracture curve which is safely higher than the stored energy curve for the diameter considered, does in fact cross it for

very large structures of the order of 1,000 ft diameter, and in such a case, catastrophic ductile failure would become possible. It was fractures of this type that probably occurred in the pressurized hulls of the Comet aircraft some years ago.

With regard to the initiation stage, it is, unfortunately, difficult to be more than qualitative. However, it can be said that the conditions for initiation are generally more severe than for propagation, because not only is a low temperature necessary but also a flaw of some type and a high local stress. Tests on the ability of various types of flaw, e.g., lack of fusion, cooling cracks, or slag, have been made but no simple relation between a type of flaw and ease of initiation is as yet emerging. The critical requirements for initiation are unquestionably linked with the local stress field and broadly a stress of the order of the yield point in the neighbourhood of the flaw is necessary to initiate a crack. Such a stress may be directly applied or may arise as a result of some gross stress concentrating feature of the design. Either way, the flaw will give rise to a further stress concentration at its tip.

Atomic Mechanism

The basic theory of brittle fracture has been rapidly developed over the past few years by Cottrell, Petch and others (see, for example, ref. 2) and the present position is briefly summarized.

Basically the theories rest upon the classical work of Griffiths, who studied the fracture strength of glass as a function of the maximum size of flaws or micro-cracks present. He found that for a given stress, σ, there was a critical size, $2L$, below which a crack would remain stable, but above which the crack would open up indefinitely and the material fail. The relationship between stress and size is

$$\sigma = \sqrt{\frac{2E\gamma}{\pi(1-\nu^2)L}}$$

where γ is the effective surface energy of the material and E and ν Young's modulus and Poisson's ratio.

This theory can be applied to any truly brittle material. Its application in the case of brittleness in steel is not so straightforward since flaws of sufficient size are not normally present and plastic yield provides an alternative mode of deformation.

However, the appropriate analysis starts with the important observation reported by Low[3] that steel will yield in compression at just the same stress as it fractures in tension. It is deduced that the cracks necessary to the Griffiths theory must be formed by the dislocation movements which occur at the lower yield stress and which would result in plastic deformation in a ductile sample. This stress is grain size dependent and is given by

$$\sigma_y = \sigma_i + k_y d^{-1}$$

where σ_i and k_y are constants proportional to the frictional force on moving dislocations and to the pinning of stationary dislocations respectively, and d the grain size.

A possible crack forming process in which dislocations lying in different slip planes combine to form cleavage cracks at the lower yield point has been proposed by Cottrell. The crack can be up to the grain size in length, and will then initiate a brittle crack if the stress obtaining in the material satisfies the Griffiths equation. A detailed analysis leads to the now well-known relation

$$(\sigma_i + k_y d^{-1})\, k_y = \beta\, \mu\, \gamma$$

for the critical conditions, where μ is the shear stress and β a numerical factor of the order of unity. If the left-hand size is greater than the right, as at low temperature, the material is brittle and if vice versa, as at high temperature, ductile.

The embrittling effect of neutron irradiation, which will be discussed later, comes about because σ_i is raised by the point defects introduced into the lattice by fast neutron collisions. This increases the left-hand side of the relation and consequently increases the temperature at which the two sides become equal.

Pressure Vessel Safety

There is no doubt that brittle cracking, considered in terms of the number of steel ships, storage tanks, pressure vessels, turbine shafts, etc., which are running satisfactorily, and have been for many years, is a rare phenomenon. However, in view of the serious consequences attending a crack in a nuclear vessel, it is inadequate to rely solely on the improbability.

It appears at first sight that the safe running of a pressure vessel can be guaranteed in either of two ways: by the prevention of the initiation of cracking, or, by the prevention of propagation.

Prevention of Crack Initiation

The elimination of conditions necessary to the initiation of a fracture would involve:—

1. The removal of all notches and cracks. It is well known that it is difficult, if not impossible, to produce welded joints in thick plates that are completely free from even the smallest crack, though the quality of welding and the rigour of the examination of reactor vessels will undoubtedly lower the number of such defects considerably. There are many welds which it is almost impossible to test ultrasonically and in which fine, inclined cracks would escape radiographic detection. Reliance on the elimination of cracks cannot be accepted as providing absolute safety.

2. Much can be done to reduce the incidence of residual stresses by careful design and manufacture and by stress relief. It does not seem possible to be certain that under no condition will any stress exceed about three-quarters of yield. The safety level required is not yet known with any certainty for the complex condition obtaining, and experiments are being planned to give guidance on this. Experiments on brittle patches welded into an experimental spherical vessel[4] have shown that under very adverse conditions cracks can initiate a brittle failure at stresses under half the yield stress. As with reliance on flaw detection, reliance on low design stress cannot, therefore, be an absolute safeguard.

Prevention of Propagation

The alternative approach is to prevent the propagation of a crack even if conditions for its initiation were possible. At low temperature, a structure will not propagate a crack unless the stored energy is adequate. Experimental work points also to the existence of a critical stress below which a brittle crack cannot propagate, though it seems likely that this stress is related to elastic energy requirements rather than being a critical stress *per se*. Robertson[5], for example, finds that at temperatures of the order of 40°C below the transition temperature this critical stress varies from about 2-4 ton/in². Even lower critical stresses have been observed in the Wells test. Kihara and Masubuchi[6] found propagation at a stress of 1½ ton/in². Thus the stress needed for fracture is, like the energy, exceeded in practice.

The above arguments lead to the conclusion that the initiation and subsequent propagation of a brittle fracture in a reactor pressure vessel is a very real possibility so long as the steel is at a temperature at which it can behave in a

brittle manner. The only means of obtaining absolute safety is by maintaining the vessel above the temperature below which brittle cracks can be propagated so that only ductile cracks are physically possible. This conclusion has been widely discussed over the past three years and is now gaining acceptance. The matter very naturally arose at the recent Symposium on Steels for Reactor Pressure Vessel Circuits held in London, when Cottrell[7], in a paper discussing the " fail-safe " philosophy with respect to brittle fracture, expressed much the same views.

In normal use the vessel will be at a high temperature and any reasonable steel will be relatively immune from failure. The effect of the neutron flux is to raise the transition temperature of the steel and thus if during a shut-down the vessel cools, it may go into a brittle temperature range. This must be considered to be a dangerous situation, particularly if the full operating pressure is maintained.

The problem resolves itself into the specification of the safe temperature requirements of the vessel in terms of its intended usage. This involves the choice of suitable methods for measuring the transition temperature of the steel used and the assessment of the effects of irradiation.

TESTS FOR BRITTLENESS

Over a dozen different tests designed to measure the temperature dependence of fracture behaviour are in current use. Each of these tests yields a temperature above which the behaviour of the specimen is essentially ductile, and below, brittle. As we have seen, a fracture can be considered to occur in two stages, initiation and propagation. The critical temperature for propagation can be defined fairly easily in an experiment, but the definition of a test to determine an initiation transition temperature is not possible owing to the variable conditions under which initiation can occur. Holliday and Noone[8] have recently quoted results showing appreciably higher transition temperatures for large-scale Tipper specimens than obtained with Charpy V-notch specimens. A further series of results obtained at Culcheth Laboratories is illustrated in Fig. 3. In each case the data correspond to the 50% fibrous condition.

We have shown that we must concern ourselves with tests which determine the propagation transition temperature of the steel. Such a test will necessarily use test pieces of full-plate thickness in order to eliminate any size or geometrical factor, and to take account of the variation of properties across the thickness. Furthermore, the test piece must be large so that the ability or inability of the plate at the test temperature to propagate a crack is clearly resolved. Such tests can be subdivided into those in which the crack is initiated in the material itself as part of the test (e.g., large notch tensile test) and those in which a running crack is started in an intentionally brittle region and runs either across a weld or up a temperature gradient into the test piece proper, which is observed either to propagate or to arrest the crack. The authors feel that the latter type of test is more clearly one which measures propagation characteristics alone. The former type of test must to some extent demand suitable conditions for initiation hence, perhaps, more severe conditions than those for propagation.

The test of the purely propagation type on which most experience has been gained is the Robertson "crack arrest test." The crack in this test is initiated in the end of the test piece which has been sufficiently cooled to be quite brittle. The standard procedure is to maintain a temperature gradient along the specimen and to take the temperature at the point of arrest of the brittle crack. This is not a simple definition since the brittle crack ends not at a straight line but at a so-called thumbnail profile, see Fig. 4a. This is probably a result of the greater triaxial stress in the centre of the plate than at the surface, where one of the stress components must be zero; the crack probably advances with a curved front. Owing to the stress condition at the surface, a shear-lip, about 0·020 in wide, is always present. Any differences in metallurgical conditions through the thickness of the plate usually give worse properties at the centre, and would therefore make the arrest profile even longer.

The interpretation of this thumbnail arrest varies. Robertson noted that the point at which gross yield first occurred at the surface coincided with the focus of the thumbnail curve, and defined this focus as giving the arrest temperature. In later work it has been more usual to take the point at which the shear-lip begins to thicken. Apart from these differences in interpretation there may be some form of " inertial " overshoot of the brittle crack, i.e., it may not stop immediately on reaching a region in which it cannot travel indefinitely.

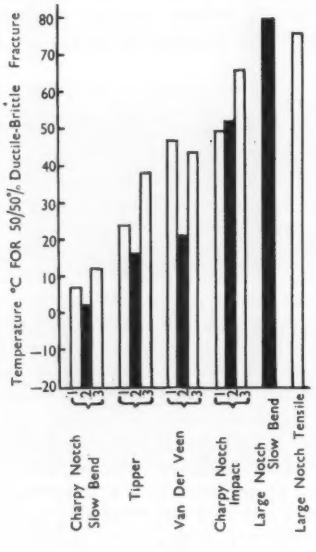
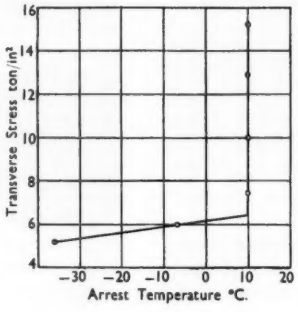
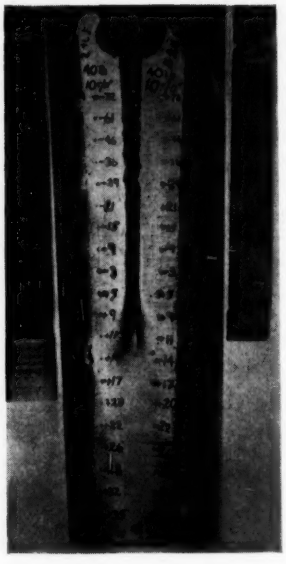


Fig. 3.—(Left) Comparison of transition temperatures obtained by different testing techniques on specimens machined from one as-rolled Si-killed steel plate, showing the effect of specimen size and strain rate.

Fig. 4.—Typical results from Robertson tests on a reactor pressure vessel steels. (a) (Right) Fracture surface. (b) (below) Variation of arrest temperature with stress.





It is these considerations which indicate that measurement of the propagation temperature must be by a test without a temperature gradient. A test similar to the Robertson test can be carried out under approximately isothermal conditions, apart from the initiating end of the test piece which must be over-cooled to be quite brittle. The length of such a specimen must be sufficient to ensure that the crack can be arrested in the constant temperature region. The gradient test is still valuable as a means of giving guidance to the best temperatures for isothermal testing.

Whilst we consider that the Robertson isothermal test is the most appropriate for assessing the quality of plate with respect to its toughness, it cannot possibly be adopted as a routine check on each plate going into a vessel on account of the size of specimen required and the cost and time involved in carrying out such a test. For a routine check, a smaller and simpler notch ductility test is necessary and it has to be assumed that if a plate satisfies the small-scale test specification, then the Robertson propagation temperature would be down to the required value, and vice versa. An obvious choice for quality control is the Charpy V-notch test which is well established and relatively inexpensive.

A typical procedure would be first the choice of a steel in terms of the design requirements of strength, oxidation resistance, etc., and average transition temperature of the steel, bearing in mind the operational characteristics of the station, followed by the laying down of a precise Robertson temperature specification for the plate. If then a number of plates, preferably from different casts, are tested both by the Robertson test and by a simple test, e.g., Charpy impact test, it should be possible to get some indication of what Charpy specification would serve to reject plates unsatisfactory with regard to their crack propagation behaviour.

This procedure clearly has its limitations, since it is known for example that correlations between different tests are generally poor, partly because the different types of notch ductility test measure different, but possibly related, phenomena. Nevertheless, these criticisms are far from unequivocal in the case outlined above, where the plates do not differ widely in composition and heat treatment, but only show the metallurgical differences which can arise between different plates made to the same specification. In such a case any undesirable variation in the metallurgical processing would affect the grain structure, solid solution or precipitation characteristics, and produce related changes in the Charpy and Robertson values.

A series of tests has been carried out in the United States by Feely *et al.*[9] using the "Esso brittle temperature test," a propagation test not dissimilar to the Robertson isothermal test. That there is some relation between this test and Charpy testing is clearly seen in the results (Fig. 5). Restriction of data to a more limited class of steel (e.g., production scatter on one steel) is expected to lead to a much smaller range of results, and correspondingly to a smaller scatter. Closer correlation between the two methods should then be possible.

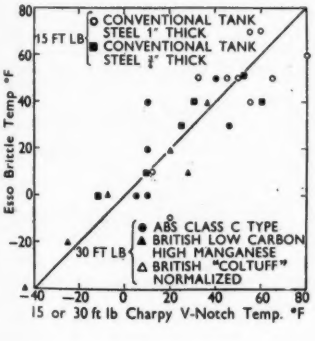


Fig. 5.—Comparison of Esso propagation arrest temperature with Charpy V-notch impact temperature. (After Feely et al.[9])

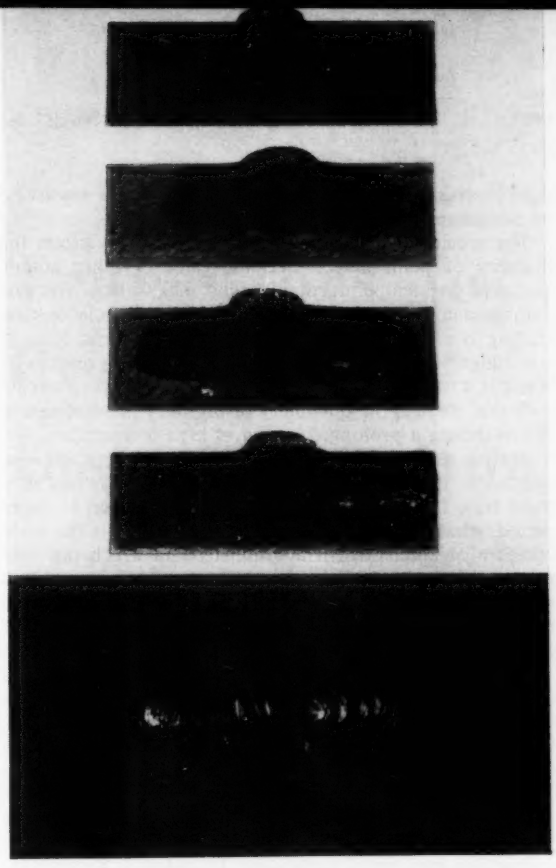


Fig. 6.—A series of drop-weight test specimens.

There are other, and simpler, tests which it is believed may well give the propagation transition temperature and might, after further investigation, provide direct substitutes for such large-scale tests. One of these is the method described by Hull[10] in which a Charpy specimen with a brittle nitride case is broken. The crack initiates in the case and enters the steel as a running crack. The other test of interest is the drop-weight test of Pellini[11] which is carried out on the type of specimen shown in Fig. 6, with a brittle weld bead on one side. The sample is bent in impact by a fixed small amount and the form of cracking determines the NDT—nil ductility temperature. This test is widely used in the U.S.A., being modest in material requirements and rapidly executed. It was reported at the Iron and Steel Institute Symposium (see also ref. 12) that NDT +60°F is now a commonly specified temperature limit for guaranteed freedom from brittle fracture and it is reassuring to note that tests at Culcheth U.K.AEA Laboratories show that this figure tends not to differ significantly from the Robertson isothermal temperature.

EFFECT OF NEUTRON IRRADIATION

It is now well known that the neutron irradiation of a steel causes its transition temperature, as determined in small notch bend tests, to rise. This is usually accompanied by a reduction in the energy of ductile fracture. The degree of embrittlement or rise in the transition temperature is not linear with dose but rises rapidly at first and then tends to level off. This behaviour is shown clearly in the work of Churchman and others[13] who took En.2 mild-steel samples to various irradiation doses and subsequently measured the transition temperature on sub-size Hounsfield impact specimens. The variation of the 10 ft/lb level with dose is shown in Fig. 7.

The relationship between embrittlement and the neutron

dose received is not simple; three other factors must also be considered.

The specimen temperature during irradiation affects the mobility of point defects and the rates of other atomic changes. At temperatures of about 300°C and over the damage can be expected to anneal at an appreciable rate, leading to a lower degree of embrittlement. Harris, Nichols and Judge[14] conclude that the embrittlement rate reaches its worst at a temperature between 130°C and 290°C. Coupled with this, there is the possibility of ordinary thermal ageing effects during a prolonged period at high temperature.

A given dose may be expected to produce more damage, and hence embrittlement, when given by a high flux in a short time than when given by a low flux over a longer period, when some annealing may occur. This is the main criticism of accelerated irradiation tests in which the dose rate may be some 100 times greater than that expected in pressure vessels. They do, however, provide a pessimistic rather than optimistic estimate of the embrittlement to be expected.

A neutron must have energy over about 500 eV before it is able to produce defects in the steel lattice, and the amount of damage increases rapidly as energy increases. It is believed that most embrittlement is caused by the group of neutrons with energies over 1 MeV in spite of the greater dose of neutrons with energies between 500 eV and 1 MeV and, if this is so, the very high energy end of the spectrum is the most relevant to this discussion.

It is thus seen that the true dose dependence of embrittlement will be a complex function. However, the experimental indications are that it will be represented by a monotonically rising curve with a continuously decreasing slope, perhaps eventually becoming horizontal. The current physical picture gives no reason to expect any other behaviour.

It should be noted at this point that the measurements of embrittlement made experimentally are normally on small specimens in which mainly initiation is involved, whereas it is a propagation test-piece which ought, in fact, to be studied. At the moment it is necessary to make the assumption that the embrittlements occurring in the two types of case are equal. Recent results by Hawthorne[15] go some way toward confirming this assumption. He irradiated Charpy specimens and Pellini drop-weight specimens and compared their respective degrees of embrittlement. His results, shown in Fig. 8, show good agreement.

Cottrell's theory of brittle fracture contains just one factor which is likely to be influenced by neutron irradiation damage. This is the term describing the resistance σi experienced by a dislocation as it tends to move through the lattice, and will clearly be affected by the increased lattice disorder brought about by fast neutron knock-on collisions. Neutrons with energies less than a few hundred eV have insufficient energy to cause lattice damage. The work on En.2 steel has shown that on this basis, after a fast neutron dose of ϕt, a rise in transition temperature of ΔT is to be expected, where

$$\Delta T = A\,(\phi t)^{\frac{1}{3}}$$

The coefficient A will depend on the type of steel involved.

An examination of the data available on embrittlement has led to the adoption of the following relation for present estimates of irradiation embrittlement.

$$\Delta T = 55\ (\phi t)^{\frac{1}{3}}$$

being measured by sulphur activation and expressed in units of 10^{18} n/cm^2. This relation is not derived from the mean of the results available but is a pessimistic, i.e., safer estimate.

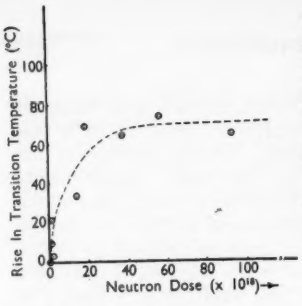


Fig. 7.—The embrittlement of En. 2 steel by neutrons. (After Churchman et al.[13])

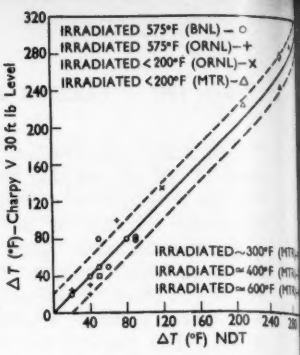


Fig. 8.—Correlation of Charpy V-notch and drop-weight tests on several steels after irradiation. (After Hawthorne.[15])

Application

The foregoing arguments have shown that it is wise to keep a reactor pressure vessel above a critical transition temperature. The Robertson wide plate test is a suitable means for defining this temperature; such tests are in fact now being carried out for the evaluation of reactor steels. For quality control Charpy tests are satisfactory, provided they are at some stage studied in conjunction with the Robertson test. During the running of the reactor, additions must be made to the safety temperature to allow for ageing and irradiation embrittlement. Different materials are present in the pressure circuit and these may show different degrees of embrittlement during service as well as having different initial notch ductilities. To avoid setting an unnecessarily high safety temperature, it is desirable that this temperature be estimated separately for each component and the highest adopted as the overall limitation.

Although initial estimates of embrittlement are made on the basis of only limited accelerated-dose experiments, these estimates will be modified during running by the results of monitoring tests on samples of the pressure vessel material put into the reactor before start-up at positions where they will be subjected to similar temperature and irradiation. Some details of the monitoring specimens in the Calder and Chapelcross reactors have been described recently by Harris, Nichols and Judge[14].

The philosophy of brittle fracture we have outlined above is now being applied to the running of the Calder and Chapelcross stations and in the design and construction of the present civil nuclear generating stations. Whilst it has been contested on the grounds that it is more cautious than the practice of conventional engineering, the principles follow the fail-safe philosophy common to all other aspects of reactor engineering.

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Transistors in Reactor Instrumentation

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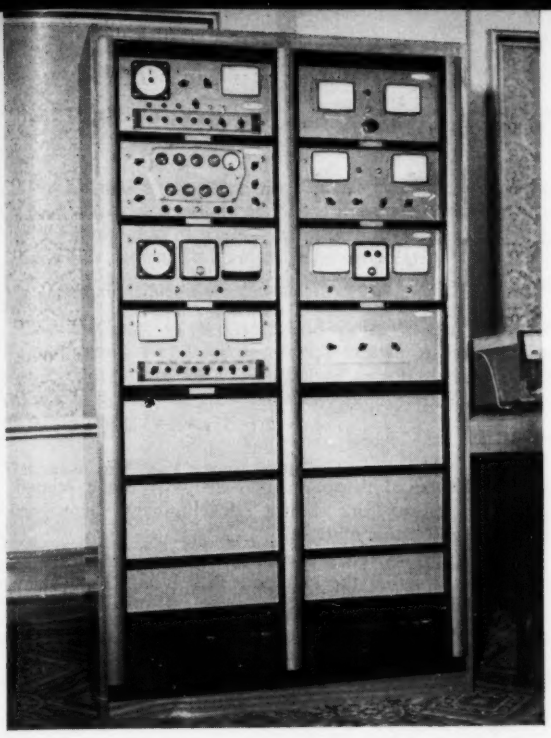

Fig. 1.—Reactor control instruments employing transistors.

THE availability and technology of transistors have advanced to a point where it has become practical to consider the use of solid state devices for reactor control. Equipment has been developed which fulfils the necessary fail-to-safety requirements when reactor safety is directly involved and provides switched outputs for incorporation in conventional interlock circuits (Fig. 1 above).

The use of transistors makes possible an indefinitely long working life as, unlike valves, transistors are not subject to gradual deterioration. Coupled with this, the transistor circuit, in general, consumes approximately one-hundredth the power of its valve counterpart, and as the space occupied is reduced by a factor of approximately ten, it follows that the heat per unit volume is only one-tenth of the valve equivalent. As a result, an enhanced reliability can be anticipated from reactor instruments incorporating transistor circuits.

Reactor control at power requires the monitoring of neutron flux (by ion chambers) and physical parameters, notably temperature (by thermocouples). For low power operation, pulse counters will be used for the determination of neutron flux. At power then measurements are d.c. and fall into two groups the detectors being low current, high impedance sources or low voltage, low impedance sources.

The range of input currents generated by ion chambers varies from 10^{-12} A to a maximum of 10^{-4} A. In the lower power ranges pulse counters will be expected to operate from 10 count/s to a maximum of 5×10^5 count/s.

Overall, in terms of neutron flux, this would correspond to 3 n/cm²s to a maximum of 10^{10} n/cm²s at the measuring point, making the total coverage 10 decades of neutron flux, which is accommodated by making use of both logarithmic and switched linear range instruments.

A basic requirement in reactor instrumentation is the amplification of small voltage signals of the order of 10 mV where it becomes essential to reduce drift to very low values. In general this can best be achieved by the use of some form of modulator which in the past has usually been provided by an electrically driven switch operating at 50 or 400 c/s. In recent years, the action of converting the input direct current signal into an alternating signal which may be readily amplified bas been performed by transistor circuits.

The Transistor Modulator

The transistor modulator or chopper[1,2] is connected into the input circuit of the measuring unit so that the alternating signal derived from the output has a peak to peak amplitude equal to the magnitude of the applied d.c. signal. The phase of the alternating signal is determined by the polarity of the applied d.c. potential. Generally the collector of the transistor is earthed while the signal is applied to the emitter; an a.c. reference signal is connected to the base terminal. Under operating conditions the transistor is driven hard into conduction for negative half cycles of the applied reference signal, thus causing the input signal to be grounded. For positive half cycles the transistor is cut off and the input signal released from earth.

As, unlike the mechanical switch, the transistor takes only a small reference power, it is practicable to operate the transistor at a high frequency, power being derived from some form of transistor oscillator. Higher switching rates are very often required when rapidly varying signals are to be measured, or under conditions where mains pick-up is to be avoided.

Both germanium and silicon transistors may be used as modulators. In general, silicon transistors provide a higher stability but, due to large base-emitter capacity coupled with hole storage effects, give rise to large voltage transients on the input wave form when operated at a high frequency. Germanium transistors do not suffer from voltage transients as the base to emitter capacity is generally small. However, the high collector leakage current of germanium transistors normally limits the accuracy of chopping and gives rise to some voltage drift. As a compromise between these types, surface barrier transistors may be employed with quite good results.

In order to obtain high stabilities the modulator should be driven from a stabilized reference source which may readily be obtained by use of a zener diode. When very small drifts are required the transistor temperature may be stabilized by enclosing the chopper in an oven maintained at a constant temperature in excess of ambient. The resulting effect is to increase the absolute value of leakage current although holding it constant, but this can lead to errors when operating with a relatively large source impedance. For reactor components this technique is not normally employed as the unit should be designed to fail to safety and this condition cannot be obtained using compensating methods.

Provided care is taken in the choice of the transistor to be used for the modulator, stabilities as shown in Table 1 can be obtained. From these drift figures it can be seen

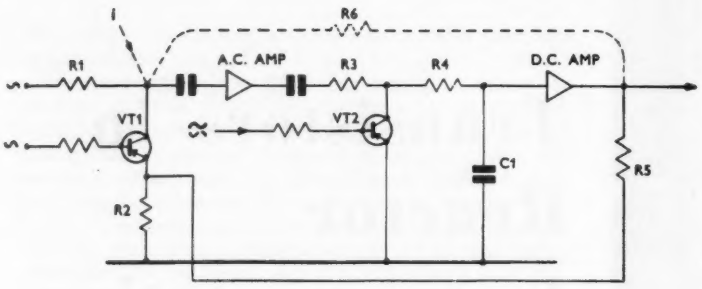

Fig. 2.—Thermocouple amplifier employing a transistor chopper.

that as a voltage modulator small drifts may be obtained, although for reactor application, as only a single sided input circuit may generally be used if the unit is required to be fail safe, the normal accuracy limit will be fixed at 100 μV. This figure is achieved also only when the source impedance is small, for example 1 kΩ. These conditions may readily be obtained for temperature measurements employing thermocouples when the input impedance is

TABLE 1

Type	Voltage stability, μV		Current stability, A	
Germanium	One transistor single sided input	100	Alone	10^{-8}
	Balanced input	10		
	With temperature stabilizing	5	With temperature stabilizing	10^{-9}
Surface Barrier	One transistor single sided	80	With temperature stabilizing	10^{-10}
Silicon	One transistor single sided	80	With neutralizing of voltage transients and temperature stabilizing	10^{-11}

small, but under these conditions the error due to modulator drift may still be in excess of 2·5°C.

Some present trends in control require a degree of accuracy that does not fall within the scope of the conventional transistor chopper, and for such purposes an alternative modulator with a much lower drift characteristic, such as a photo-sensitive modulator, must be employed. In this, a light source of alternating strength causes the impedance of a photo-sensitive element to change from a high to a low level. Some investigations have recently been carried out into the problems which exist with this device, including the availability of a suitable light source which is capable of switching a photo-sensitive crystal. Techniques involving polarization or refraction are bulky and costly and the only satisfactory method of obtaining modulated radiation is by the use of a light source which may be readily switched on and off. Of the three types of light emitter available, incandescent (tungsten filament), gas discharge (argon-neon, etc.) and electroluminescent, only the last constitutes a solid state source. The others suffer from the disadvantages of limited life, and intensity and spectrum problems.

The most promising device would appear to be the junction diode operated under avalanche conditions, which seems to have an indefinite life owing to the non-destructive nature of the phenomenon[3, 4, 5]. However, many experiments have yet to be carried out before its use as a reliable modulated light source can be assessed.

The properties required of a photo conducting material[6] when operating as a low level chopper in conjunction with a modulated light source lead to the choice of two materials, cadmium sulphide and cadmium selenide. The former, though slower in response, is by far the more sensitive, speed of response and sensitivity being related; for this reason the major development has been concentrated on this material.

The conclusions reached during tests on photo-sensitive modulators are that the chopping rate is limited to some 2 c/s so that for all practical purposes a chopper-corrected type of amplifier will have to be employed in order to maintain a sufficiently large bandwidth for general use. With careful design the modulator may provide a voltage stability of 2 μV and a current stability of 10^{-11} A. Further investigation has yet to be carried out in order to ascertain if the combination of CdS and the p-n junction in avalanche is a practicable proposition.

Thermocouple Amplifier

The transistor chopper or photo-sensitive modulator may be used for the modulation of signals received from thermocouples. Such a unit is shown in Fig. 1 which illustrates the use of a silicon transistor chopper connected into an amplifier whose characteristics are listed in Table 2. The circuit shown provides a constant current output which makes it particularly useful when several meters are to be energized. A voltage output may be obtained by connecting a suitable fixed feedback resistor R5; zero suppression and cold junction compensation may also readily be added. The high input impedance may be utilized to average a number of thermocouple inputs. If the unit is required to amplify current inputs the circuit may be arranged as shown by R6; under these conditions a virtual earth input is obtained. By small modification the unit may be converted into a thermocouple trip amplifier.

TABLE 2

Input f.s.d.	10 mV
Output	1 to 10 mA
Load	0 to 500 Ω
Drift	100 μV long term
Input Impedance	30 kΩ

Thermocouple Trip Amplifier

This unit has been designed to be fail safe under component failure conditions. The amplifier employs an a.c. carrier technique which utilizes a transistor chopper as a modulator. The resulting a.c. signal is amplified by use of a three stage transistor amplifier which, although used as an a.c. amplifier, is direct coupled and provided with d.c. feedback. The use of the direct feedback serves to stabilize the operating point of the amplifier and at the same time fixes the a.c. gain at the desired level. The direct coupled stages also have the advantage that the amplifier may be set to the correct operating point using bias obtained from the trip level reference voltage. In this manner the amplifier is either cut-off or saturated for any type of reference component failure, thus causing the amplifier a.c. output voltage to return to zero.

The normal a.c. output, after phase sensitive detection, is used to hold a polarized relay energized. Should the input signal equal or exceed the trip setting the output d.c. level either returns to zero, or reverses polarity. In either case the polarized relay de-energizes and a trip condition results.

The unit may be converted into a current trip amplifier by employing a suitable measuring resistor. This system may be adopted when the output of an ion chamber is to cause trip operation, provided the input current is equal to, or larger than, 10 μA.

Detection of Low Current Signals

The measurement of small direct currents from high impedance sources presents a special problem with transistor circuits which are essentially low impedance networks. It becomes necessary to provide some device which matches the high input impedance of the source to the low impedance transistor amplifier, and yet provides a very small current drift. In some circuits an electrometer valve may be employed although this is not always suitable; it is not possible readily to make the circuit fail safe as is required in shut-down amplifiers. For fail-safe operation it is usual to employ some form of a.c. carrier system using a chopper or modulator.

Such a modulator employing solid state devices operating in conjunction with a transistor amplifier and obtaining an impedance match between the high source impedance and the low input impedance of the amplifier is shown in Fig. 3.

The input impedance to the bridge is about $10^9\ \Omega$ which is maintained at this high value provided that the diodes are not forced into conduction. The output transformer is so designed that it is resonant with the effective bridge capacity at the applied reference frequency; this prevents any bridge loading. The a.c. impedance of the bridge is low at the reference frequency of 100 kc/s so that the impedance present at the secondary of the output transformer is about 10 kΩ.

The modulator described forms an impedance transfer from $10^9\ \Omega$ input impedance to $10^4\ \Omega$ output impedance. With careful design and construction the drift of the bridge may be reduced to 10^{-11} A for an ambient temperature range of 30°C. In a modified version of the circuit the system may be made self oscillatory and this type of amplifier can provide stabilities of 10^{-12} A when the ambient temperature is maintained at a constant level.

This low current drift makes the device ideal for the detection and amplification of signals derived from ion chambers, and may well serve as a deviation amplifier or as a logarithmic amplifier over the restricted range normally associated with health monitoring equipment.

As the unit functions on an a.c. carrier system it may be modified to form a shut down amplifier. The trip level required is set by injecting a current into the bridge modulator from a preset voltage reference. This input signal causes an oscillation to occur which, after detection, energizes a relay fed from the amplifier output. When the input current corresponding to reactor power level reaches or exceeds the set trip level, the oscillation ceases and the trip relay is de-energized. Any component failure in the amplifier will either cause the unit to trip, or in the event of increased loop gain the effect will be to change the on/off differential.

Pulse Counting Equipment

Pulses from nuclear particle detectors require amplifiers having a large bandwidth and high charge sensitivity. The conditions may be realized by the use of a transistorized a.c. amplifier provided with overall feedback. The d.c. operating conditions of the amplifier are maintained by direct coupled stages with d.c. feedback.

The conventional "ring of three" circuit as employed with valve pulse amplifiers may be used, with the exception that increased bandwidth can be obtained by inserting emitter followers between stages. In this manner the large base/emitter capacity is prevented from shunting the preceding collector load. The use of direct coupled stages serves to prevent blocking of the amplifier when large pulses are received and stabilizes the operating point of the amplifier for large changes in ambient temperature. By careful design the bandwidth of an amplifier having a gain of 50 may be extended to 3·5 Mc/s at the 3 dB point. A further important factor in the performance of a pulse amplifier is the effective r.m.s. noise charge sensitivity referred to the input terminal. In the circuit discussed the noise charge equivalent is 10^{-15} coulomb.

The transistor pulse amplifier has one main advantage over the conventional valve amplifier when large cable lengths are encountered between the counter and head amplifier. The noise output of the transistor amplifier is reduced in proportion to the length of cable applied to the input terminal so that for large changes in length of cable, up to a maximum of 25 ft, the signal to noise ratio is virtually unaffected. This effect does not take place with the valve amplifier where the noise component is independent of cable length, while the pulse presented to the amplifier input is inversely proportional to the length of cable. Increased cable in this case causes a decrease in signal to noise ratio.

The low input impedance, 10 kΩ, of the transistor amplifier makes the unit far less sensitive to electrostatic pick-up radiated from contactors and relays and may well prove to provide a higher degree of reliability and freedom from spurious trips in reactor operation. A further advantage is that all the power for a remote head amplifier may be carried on one concentric cable which may also be used for transmission of the amplified pulse, thus reducing the cost of cable installation.

Pulse Height Discriminator

A discriminator comprising a Schmidt trigger circuit using conventional transistors can be built with a paralysis time of 0·5 μs, the resulting rectangular output pulse triggering an Eccles-Jordan binary counter which provides a 2·5 V output pulse. The discrimination level is made adjustable over a range of 0·2 V to 5 V which covers the normal output pulse amplitude from the amplifiers. Ambient temperature changes of 30°C cause only a 40 mV

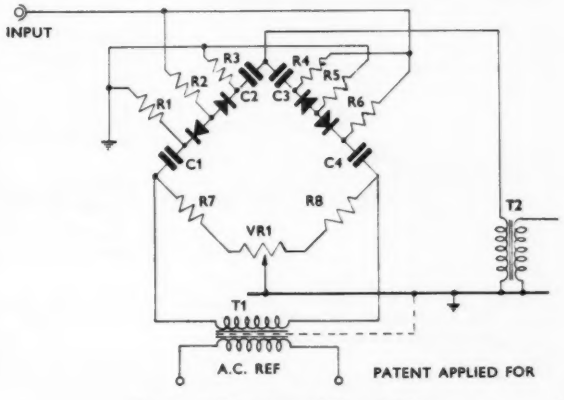

Fig. 3.—Solid state modulator bridge.

change in bias level so that 1% discrimination on pulse height is possible using such equipment.

Logarithmic Ratemeter

The logarithmic ratemeter shown in Fig. 4 comprises a pulse height defining stage followed by a series of diode pumps. Each pump employs silicon diodes in order to obtain low leakage characteristics and has a built-in response time defining network C_2R_1, etc. In this way the response of the unit may be made variable over the entire logarithmic range. The output currents from each of the diode pump sections are summed to provide a continuous indication of count rate over a range of some 5 decades from 1 count/s to 10^5 count/s. The summed current at full scale deflection is 50 μA and for convenience this is amplified by use of an electrometer/transistor amplifier to form a full scale output of 5 V.

The pulse channel provides a very compact counting equipment and has been found to give reliable results when tested on nuclear reactors.

D.C. Trip Units

In order to provide trips and alarms for high flux, low flux, and period signals, it is necessary to provide units which will monitor the d.c. output voltage either from the ratemeter amplifier or any d.c. output dependent on flux levels. These basically comprise a comparator stage using two transistors connected as a "long tailed pair." The common emitter current is defined by a third transistor serving as a high impedance source.

The independent variable signal corresponding to flux or period information is connected to one base whilst a reference signal, preset to the trip level required, is connected to the second base. A transistor trigger circuit is driven from the output of the comparator; under safe conditions a relay is energized but is de-energized when the input exceeds the preset trip level.

Complete Pulse Counting Channel

A complete pulse counting channel is given in Fig. 5, which illustrates the breakdown of units and the general facilities provided. The total power consumed by the transistor channel is approximately 15 W as compared with 400 W for a conventional channel. The space occupied is also reduced by a factor of about four.

Fail Safe Transistor Logic

The use of solid state devices has also been applied to logical circuitry, and alternating voltage operated transistor logic may be provided by the use of the p.n.p.n. transistor which may be made fail-to-safety.

The four layer three terminal p.n.p.n. device is connected into a circuit which is so built that the a.c. applied to the base connection is of sufficient amplitude to switch the device from the conducting state to a "cut-off" condition. As the p.n.p.n. switch is a trigger device it will remain conducting, once switched, until receipt of a reverse polarity base pulse. If the applied a.c. is biased by an input voltage direct coupled via the resistor shown, it is possible to prevent the device either switching on, if initially "cut-off," or vice versa. In this manner the a.c. output will be present when the d.c. level is below a predetermined value and will cease when the d.c. bias is increased. If the bias is dependent on a flux signal the loss of a.c. output may correspond to a high flux trip. The circuit may be made to "store" trip conditions by rectification of the output a.c. signal and feeding the resultant d.c. back to the base electrode. If the rectification used is made phase sensitive the system becomes "fail safe" as any failure of components will cause either no a.c. output or an output which is 180° out of phase with the reference to the detector.

As the device is used as a switch, large currents are available to drive subsequent switches and control gear.

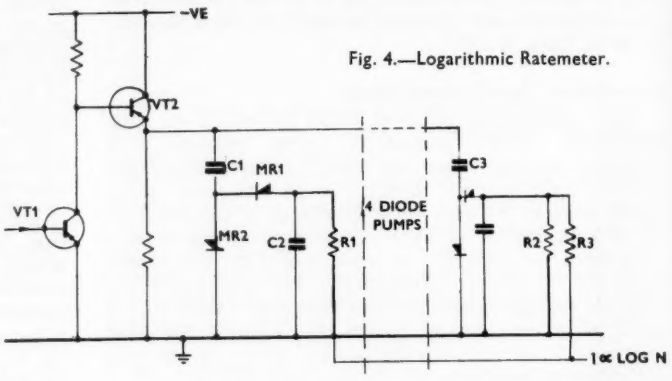

Fig. 4.—Logarithmic Ratemeter.

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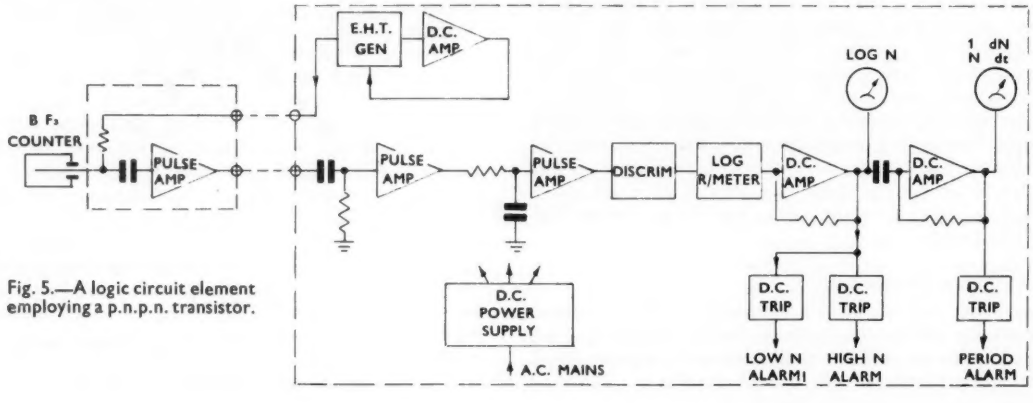


Fig. 5.—A logic circuit element employing a p.n.p.n. transistor.

Personal

Appointments

The new chairman of the U.S.AEC is **Dr. Glenn Seaborg,** chancellor of California University and associate director of the Lawrence Radiation Laboratory. In 1951, Dr. Seaborg, who is 48, was awarded the Nobel Prize for his discovery of plutonium. His predecessor at the AEC, Mr. John McCone, is returning, it is understood, to the position of president of the Joshua Hendy Corporation, a Los Angeles shipping company.

Mr. Charles H. Weaver, vice president in charge of nuclear power for Westinghouse Electric Corporation, has been elected president of the U.S. Atomic Industrial Forum.

Mr. Roy G. F. Gross, an engineer and ex-Canadian Air Force Officer, as general manager of the Canadian Nuclear Association.

Mr. Charles V. Bulck, formerly assistant administrative manager, U.S.AEC Oak Ridge Operations, becomes manager of procurement for AMF's Government Products Group.

Mr. T. B. O. Kerr.

Mr. E. H. Davison.

Dr. Louis Werner, for over two years London representative of the U.S.AEC, has returned to the States to become a vice-president of the Hazelton-Nuclear Science Corporation, Palo Alto, California.

Mr. Edward D. Kendrick, Jr. and **Mr. Thomas V. Wambach,** to the Allis-Chalmers nuclear power department, Washington, D.C.

Dr. Alvin M. Weinberg, director of Oak Ridge National Laboratory, has been requested by President Kennedy to continue serving on the Science Advisory Committee.

Dr. Howard Reiss, as associate director of the research department at Atomics International, Canoga Park, California.

Mr. Charles F. Dickson, a director of Crompton Parkinson, as vice chairman.

Mr. J. M. Harris, as managing director of Holland & Hannen and Cubitts (Great Britain).

Mr. T. B. O. Kerr, director for finance and administration of the GEC, as deputy managing director. **Mr. E. H. Davison,** previously treasurer of Courtaulds, becomes financial director. Both Mr. Kerr and Mr. Davison are members of the new GEC management committee. Other members are **Mr. Arnold Lindley,** chairman, **Mr. O. W. Humphreys,** and **Mr. R. N. Millar.**

Dr. Glenn Seaborg.

Mr. Chas. H. Weaver.

Mr. Roy G. F. Gross.

Mr. Chas. V. Bulck.

Mr. David R. Toll, staff legal adviser to the U.S. Congressional Joint Committee on Atomic Energy, as special assistant to **Mr. Sterling Cole,** director-general of the IAEA.

Sir Joseph Latham, formerly deputy chairman of the NCB, as director of finance, AEI.

Mr. Arnold Lindley, GEC chairman, is chairman of the United Power Company, the company formed by GEC and APC for the construction of nuclear power stations and which is tendering for Oldbury (last month's "World Digest"); **Lord Coleraine,** APC chairman, is vice-chairman; **Colonel G. W. Raby,** APC managing director, managing director; **Mr. H. Clarke, Mr. J. Mayer, Mr. R. N. Millar, Mr. O. J. Philipson, Mr. C. C. Vinson,** and **Dr. K. J. Wootton,** are directors, and **Dr. H. K. Cameron** and **Mr. J. W. Ashley,** joint technical directors. Secretary is **Mr. W. Adams.**

Dr. F. A. Tatford, director of contracts, U.K.AEA, has been elected as president of the Institute of Public Supplies for a second year. He has also been appointed a director of the National Institute of Governmental Purchasing, Inc., of the U.S.

Sir Leonard Owen, member for production of the U.K.AEA, is the Institution of Civil Engineers' representative on the U.K. Advisory Council on Education for Management which has been established by the Minister of Education to keep under review the provision made for management education in technical colleges.

Mr. F. J. B. Barry, manager of the GEC plant liaison department in London, as commercial manager of the Witton Engineering Works.

Following the Ekco-Pye merger it is announced that **Mr. N. A. Twemlow,** a director of Pye, has been appointed to the Ekco board, and **Mr. W. M. T. York,** an Ekco director, to the Pye board.

Mr. S. A. Clodd, works manager and executive director of E. K. Cole, to the board.

Mr. P. T. Stephens as chairman of the Saunders Valve Company. He will continue as a joint managing director with **Mr. A. L. Trump.**

Mr. A. W. Page, general sales manager of Brookhirst Igranic, as sales director.

Mr. Ll. Young, general manager of Bailey Meters and Controls, as director of engineering.

Mr. W. R. Brew, as executive manager (engineering) of Wild Barfield Electric Furnaces.

Mr. R. Cox, works manager for Low Moor Fine Steels, as an additional director of the company.

Mr. J. G. Stewart to the board of Stewarts and Lloyds. A son of the chairman, he has been with the company since 1951 and has specialized in tube production.

Mr. E. W. Embleton as manager of industrial sales for Mullard.

Mr. T. Coughtrie, as chairman of Bruce Peebles. He succeeds **Mr. S. A. Gaskell,** who remains on the board.

Mr. Kenneth Platt, deputy secretary of the Institution of Mechanical Engineers, as secretary in June.

Sir Stanley Rawson, as chairman of Harper Engineering and Electronics. He replaces **Mr. N. C. Weaver,** who has relinquished the post but remains on the board. **Mr. H. W. Bishop** becomes a director.

Mr. Rodney Kent, as deputy chairman of George Kent; **Mr. Walter May,** as assistant managing director; and **Mr. John G. Vaughan,** managing director of the Charterhouse Finance Corporation, as a director.

Mr. E. F. Coppock, financial and budgetary controller with Elliot Brothers (London) since 1957, as group financial controller of Metal Industries.

Mr. A. B. Tilleray, as sales manager of the industrial control division of Thorn Electrical Industries. He was formerly with the Sorensen Division of J. Langham Thompson.

Mr. R. J. F. Howard, as director of marketing of Metal Industries.

Captain H. A. Kidd, R.N., to be in charge of the Admiralty reactor experiment at Dounreay.

Resignation

Mr. Brian Robbins, secretary of the Institution of Mechanical Engineers since 1951, is leaving the Institution on June 1.

Retirement

Mr. J. H. B. Chapman, to retire in April as director of naval construction at the Admiralty.

Obituary

Nuclear Engineering regrets to report the death of **Professor Francesco Giordani,** chairman Emeritus of the National Council for Research, Italy. He was for four years the first president of the National Committee for Nuclear Research, established in 1952. Professor Giordani was 64.

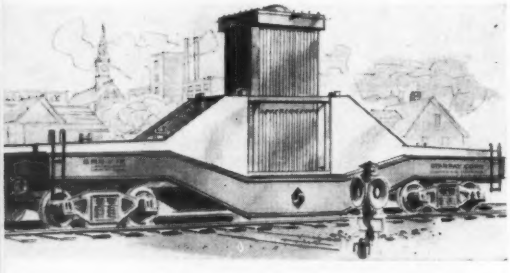
Industrial Notes

Cawkell Research and Electronics have received from the U.K.AEA contracts worth £20,000 for investigating new methods of recording waveforms. The aim is to achieve greater accuracies than were obtained with the oscilloscopes supplied for the Zeta project. The contracts include provision for investigating means of storing and processing such information.

Nuclear Enterprises (G.B.) are building a new office and factory block at Sighthill, Edinburgh, to provide extra workshop and research facilities. Costing £55,000 the block will have accommodation for 250 employees. Occupation is scheduled for early autumn. Initial development will cover 25,000 ft², but the site allows for a further expansion of 50,000 ft².

English Electric have been awarded a contract for the design and manufacture of the main propulsion steam turbines and condensers for Britain's second nuclear submarine. The keel for this vessel, to be built by Vickers-Armstrongs, is expected to be laid very shortly.

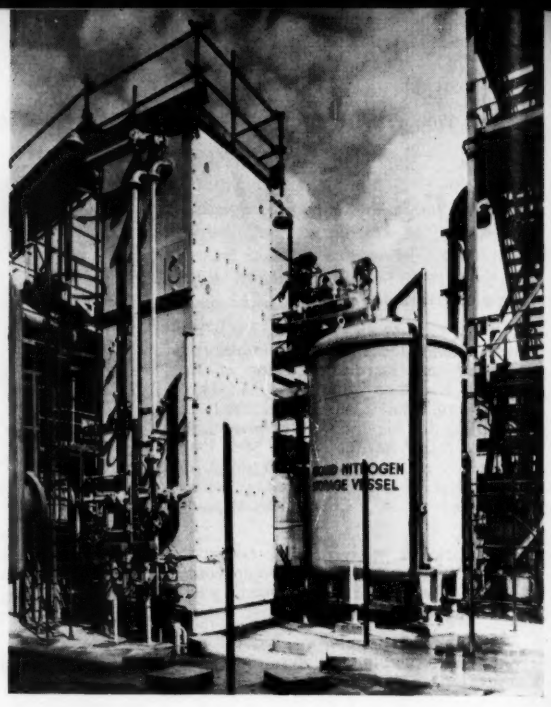
The DSIR have set up a working party to consider national needs in the field of scientific films. It is especially interested in the aspects of film as a research tool and in communicating research results. A questionnaire has been sent to industry, universities and research organizations asking for details of stock and techniques.



The Stanray Corporation, Chicago, are to build a stainless steel coffin and special rail truck for the transportation of irradiated fuel from *N.S. Savannah*. The company will also be responsible for the operation of the unit.

Initial changes made in the administrative structure of **GEC** to strengthen the management include the establishment of a management committee made up of working directors and the appointment of a new financial director from outside the company (see "Personal" on page 121). The company has announced that provisional results from the first eight months of trading in the current financial year and estimated figures for the remaining months indicate that the profit for the 12 months will be lower than for last year.

Nine European countries were visited during February by fact finding missions organized by the **Export Council for Europe** to survey export prospects for British industry. Ten further countries will be similarly visited during May.



Part of a high purity nitrogen plant supplied by Petrocarbon Developments to the U.K.AEA. View includes the cold box and liquid nitrogen storage vessel.

Temple Press have just published an entirely new and comprehensive guide to the plastics industry. Called "*Plastics*" *International*, it provides information for both the user of plastics materials and the manufacturer. Full details of plant, materials and processes are given, including illustrations, as well as the names and addresses of manufacturers and agents. Copies, 63s. each, are obtainable from Temple Press, Bowling Green Lane, London, E.C.1.

GEC are re-organizing the Wembley Research Laboratories. Autonomous research units, operating side by side, each sharing the same scientific and administrative services, will be set up. This will enable the groups and subsidiaries of the company to have research units under their own control, thus securing a closer integration of applied research and development than in the past. To mark this change of policy the laboratories have been re-named the Hirst Research Centre. Research and development work on graphite, including its impregnation, is conducted at the laboratories.

Shawford Control Gear Company has been formed for the purpose of importing into the U.K. from Italy the CEMA range of control equipment. The address is Midland Terrace, Victoria Road, Willesden, London, N.W.10.

Two new films available from the U.K.AEA are "Dounreay Symposium," featuring highlights in the construction and commissioning of the DFR, and "Steel for Nuclear Power," about the problems attached to the development of improved steels for reactor pressure vessels. Both were made by **Ace Film Productions.**

A course of evening lectures on "The Uses and Safe Handling of Radioactive Substances" starts at the **Hendon Technical College**, London, N.W., on February 23. Details are available from the head of the mechanical engineering department.

The Vitro Corporation of America, New Jersey, announce that uranium monocarbide is now available in laboratory quantities. It is obtainable either as granules or as high density spheres from 200 mesh to $\frac{1}{16}$ in diameter in size.

De Rotterdamsche Droogdok Maatschappij N.V. (The Rotterdam Dockyard Co.) have received a contract from the International General Electric Company for the construction of the core structure of the reactor pressure vessel for the 150 MW BWR plant being built at Garigliano, Italy. The core structure, to be made from stainless steel, consists of a thermal shield, core support, core plate and top guide. Dimensions of the thermal shield: 118 in diameter, 137 in height.

General Electric have been awarded a $166,200 contract for the supply of 300 MTR-type fuel elements for the Oak Ridge Research Reactor (ORR). Delivery is expected to begin in March. ORR went into operation in mid-1958. Fuel elements in use up to now have been fabricated at Oak Ridge.

N.V. Neratoom, of The Hague, Holland, have been awarded a contract for the construction of the core structure for Dragon. The work will be shared between N.V. Machinefabriek "Breda," Koninkinklike Mij "De Schelede," and Werkspoor N.V., members of the Neratoom group.

AMF Atomics (Canada) have shipped the 273 fuel elements they have fabricated for use in the JRR-3 under construction at Tokai-Mura, Japan. The shipment contained approximately 14,800 lb of uranium metal and was worth about $450,000. A portion of the uranium used in the manufacture of the elements was refined in Canada and donated to the IAEA by the Canadian Government. The metal was then bought from the Agency by the Japanese Government. The remainder of the metal was refined in Japan and then shipped to AMF Atomics (Canada) for fabrication.

Association Belge pour le Developpement Pacifique de l'Energie Atomique a.s.b.i., 35 rue Belliard, Brussels, 4, the public relations office of the Belgian Centre for Nuclear Energy, invites manufacturers and supply companies to send in sales literature about their products and services.

H. and E. Lintott, electro-mechanical engineers of Horsham, have changed their name to Lintott Engineering.

Technical Papers and Publications

THE INSTITUTION OF MECHANICAL ENGINEERS in co-operation with THE BRITISH WELDING RESEARCH ASSOCIATION

Symposium on PRESSURE VESSEL RESEARCH TOWARDS BETTER DESIGN

IS it not high time that we revised our ideas on the methods of pressure vessel design? And, if so, what are the main factors to be taken into account when formulating new bases? This, in effect, was the theme of a symposium held by the I.Mech.E. in co-operation with BWRA.

Without considering the discussions on each session the papers alone numbered 14, aggregating well over 200 pages, and thus preclude any attempt at summarization, or even brief reference to the papers in any chronological order; in fact the best general introduction to the subject was, paradoxically enough, the final paper. In "Pressure Vessel Design Requirements in the Near Future," Dr. W. B. Carlson (Babcock & Wilcox) pointed out that no attempt to improve design methods could result in truly economic designs if minimum permissible plate thicknesses continued to be tied to arbitrary design stresses based on certain "factors of safety" applied to some property of the material such as the ultimate tensile stress or the yield point. Present-day pressure vessel design rather unrealistically assumed that vessels failed only by bursting due to overpressure or creep, and that the pressure strength of a vessel was directly proportional to some property such as the U.T.S. creep rupture strength or the yield point of the material. This single-stress approach ignored reality.

A plea was made for a new approach, basing designs on definite departures from an idealized project. An idealized pressure containment project was defined as one in which the vessel was considered as one thin, pure, geometric shape, such as a sphere or an infinitely long cylinder, having only pure membrane stressing, operating at a steady internal pressure and constant temperature, with no corrosion, and no limitations on elastic inflation with pressure. For such an ideal vessel, there was no reason why the membrane stresses should not be 99% of a suitable minimum probability value of the yield or creep rupture stress of the material at the working temperature. This, then, would be the basic design stress. For each individual departure from the ideal conditions, an appropriate stress intensification factor* should be allowed. In other words, the design stress should not be based on the automatic assumption that there would always be stress intensification of 2-2½ due to unreinforced holes or discontinuities; this merely encouraged bad design. There should, instead, be a bonus for good design and accurate construction.

In the words of Mr. R. Weck (BWRA) who reported on Papers 12-14, a vessel with a maximum stress concentration factor of 1.5 designed on a safety factor of 2 is safer than one with an SCF of 4 designed on a safety factor of 4.

Failure of pressure vessels could occur from any one of the following causes, or a combination of several:—

1. Excessive elastic deformation leading to change of shape, maldistribution of support loads, leakage at mechanical joints or instability or buckling.
2. Excessive short-term plastic deformation, leading to the same.
3. Long-term creep, leading to low-elongation creep cracking, or as in 1.
4. High strain fatigue, leading to cracking and eventual leakage or rupture.

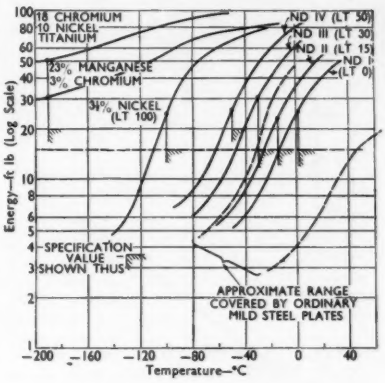


Fig. 1.—Typical Charpy V-notch impact test strengths of mild steel, notch-ductile steels and alloy steels. (Strawson, Paper 12.)

5. Corrosion fatigue, leading to the same.
6. Stress corrosion, leading to the same.
7. Fracture initiation and propagation under low applied stress (brittle fracture).

It was important to note that existing design methods did not necessarily allow for all of these, so that a vessel manufactured strictly in accordance with these rules, was not necessarily safe, since it might still fail from brittle fracture, stress corrosion or fatigue. This thought, said Mr. Weck, might be considered by those who strenuously resisted any changes in existing rules on the grounds that changes would necessarily increase the risk of failure. Admittedly, pressure vessel failures were, happily, rare, but that hardly justified ignoring 25 years of materials and design research which had quite clearly indicated the direction that should be taken to produce vessels which were not only more economical, but considerably safer.

One of the points made by Dr. Carlson was in connection with the interpretation of stress intensification. Broadly speaking, a stress intensification which involved a large cross-section must be allowed for in full, whereas an equal intensification which is highly concentrated and supported by areas of lower-stressed material is much less important. This point was also made by Dr. Rose, in Paper 11.

Pressure Tests

In his report, Mr. Weck pointed out that there was some divergence of opinion between Mr. Strawson (Paper 12) and Dr. Carlson, on the value of the pressure test. Mr. Strawson appeared to approve it because of its possibilities as a method of stress relief, whereas Dr. Carlson seemed dubious about its value, unless it was specifically designed to demonstrate prestated features of the vessel's ability. If its purpose was stress-relief, said Mr. Weck,

LIST OF PAPERS

SESSION 1

1—Calculated stress concentration factors for nozzles in spherical pressure vessels. R. T. Rose and J. M. T. Thompson.

2—Stress analysis of nozzles in cylindrical pressure vessels. A. A. Wells, P. H. R. Lane and R. T. Rose.

3—Stresses at oblique nozzles in spherical pressure vessels.
Part I: Stress analysis of a single oblique nozzle. R. T. Rose.
Part II: Stress analysis of a series of single oblique nozzles. K. G. Mantle and E. Proctor.
Part III: Stresses in oblique nozzles on pressure testing of reactor pressure vessels. R. W. Horseman.
Part IV: Oblique nozzle array in a spherical shell. A. C. Mackenzie and J. Spence.
Part V: Conclusions. R. T. Rose.

4—Comparative performance of pressure nozzles under pulsating pressure. P. H. R. Lane and R. T. Rose.

5—Pressure vessel research in Belgium. W. Soete, F. Hébrant, R. Dechaene and J. Heirman.

SESSION 2

6—Lobed pressure vessels. J. P. Duncan and N. W. Murray.

7—Right-angled corner in large-diameter pressure ducting—some experimental stress analysis results and comparisons with theory. A. C. Mackenzie and I. M. Beattie.

8—Stresses in hemispherical drum heads. H. Fessler and C. N. Lakshminarayana.

9—Behaviour of large taper hub flanges. N. W. Murray and D. G. Stuart.

SESSION 3

10—Photoelastic determination of the stress distributions in boiler-drum tube plates. J. A. Coutts and C. Snell.

11—Fatigue tests on tube plates. R. T. Rose.

SESSION 4

12—The low-temperature problem. J. W. Strawson.

13—A comparison of United States, European and British Commonwealth codes for the construction of welded boilers and pressure vessels. J. F. Lancaster.

14—Pressure vessel design requirements in the near future. W. B. Carlson.

* The majority of the papers referred to the "stress concentration factor" or SCF. Dr. Carlson, who opened the Symposium by reporting on the first five papers, made it clear that he considered that this term implied not only the ratio of maximum to mean stress, but also the space relation between them—something which could not be formulated in general terms, at the present. Until this was possible he felt that "intensification" was to be preferred. SCF and SIF are, therefore, interchangeable terms for present purposes.

one might conclude that the test should be designed to be most effective for this purpose, and carried out with warmed liquid at a higher pressure than the working pressure. If, on the other hand, its purpose was to demonstrate that the vessel was not liable to brittle fracture at the working pressure, it should be carried out at the lowest possible service temperature, at a pressure not exceeding the working value. It was doubtful whether the substitution of the pressure test for either thermal stress relief or notch-ductile steels would meet with general acceptance.

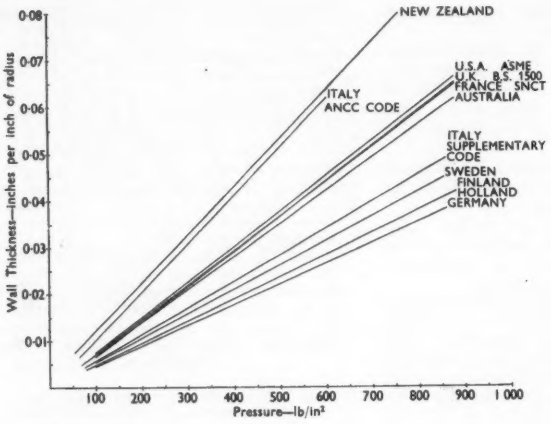


Fig. 2 (left).—Wall thickness specified by various codes for cylindrical shells subject to internal pressure.

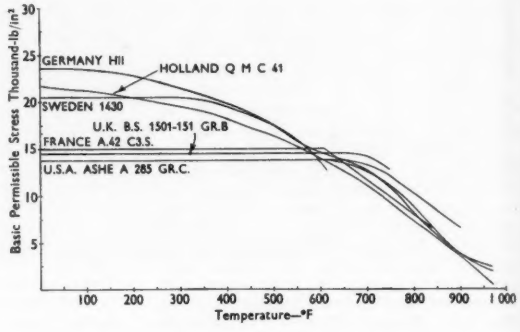


Fig. 3 (above).—Permissible stress as a function of temperature for various codes (Lancaster, Paper 13).

Brittle Fracture

If, as the summary of Paper 12 points out, pressure vessel failures have been rare despite the use of ordinary run-of-the-mill steel (which might be expected to be brittle between −20°C and 50°C) notch ductility cannot be the only factor responsible for satisfactory performance. If freedom from brittle fracture is to be obtained by choice of materials on the basis of impact tests alone, the actual requirements must be varied in relation not only to temperature alone but to other conditions of operation and construction. An impact test figure of 15 ft/lb was suggested for three classes of vessels only; those which were not stress relieved, stress-relieved vessels if the service temperature fell below certain limits fixed in relation to plate thickness, pressure-tested vessels only if the service temperatures fell below the same limits of temperature in relation to thickness (below −50°C for ¼ in thick, and below 0°C for material 1¼ in thick or over).

This view was, incidentally, criticized during the discussion, on the grounds that some steels are not satisfactory even though they give higher impact test values than the 15 ft/lb quoted. It was considered that the designer should be more generally aware of the nature of a steel in terms of crystallinity and degree of ductility at a particular temperature, rather than be bound by an empiric value.

The International Scene

A paper of considerable interest and reference value was No. 13, in which Mr. J. F. Lancaster compared the codes of some 20 countries as regards their legal status and methods of administration, with a further table comparing specified properties for carbon steel boiler plate in different countries. It was peculiar that, with so many differing requirements, standards of safety are high, and failures are rare and, when they do occur, are not normally associated with inadequate wall thickness, or deviation from normal standards of construction. It was pointed out that, in fact, this happy situation resulted more from a combination of sound engineering and commercial integrity than from any form of legal compulsion. Some idea of the wide divergence between national standards may be obtained from Fig. 2 showing wall thicknesses for carbon steel vessels: for 700 psi British practice uses nearly twice, and New Zealand 2½ times, the German codes. If, as Mr. Weck pointed out, this is considered in the light of Mr. Strawson's figures (i.e., the low-temperature risks increasing with thicker plate) one wonders whether some code-makers, in their zeal for safety, do not mistake the shadow for the substance.

An even more anomalous situation arises in relation to plate thicknesses for varying temperature. In Fig. 3 stresses permissible under various national codes are plotted against temperature. At 600°F (315.5°C) the differences between one code and another are very slight, whereas at 300°F (149°C) and 900°F (482°C), differences are quite considerable. At 900°F, for example, the U.S. permits twice the stress of the German code; at room temperature, the situation is reversed.

It is evident that, amongst other things, Great Britain is, with existing codes, in an unfavourable position for competitive work abroad. As Mr. Weck pointed out in his summary, the problem of pressure vessel codes is no longer one of scientific or technical interest; if we are to compete in export markets, their revision has become a matter of national concern.

Editorial Comment

It is regrettable that space considerations preclude discussion of what might be termed the "detail" papers in which the stress-raising properties of nozzles and discontinuities in design are fully analysed; one is, in effect sweeping aside 11 out of 14 papers. It is impossible to overestimate the importance of the work which BWRA has been carrying out during the past few years to this end, particularly in regard to the performance of protruding nozzles and "balanced" compensation, i.e., reinforcement applied to both sides of the hole. (An introduction to Dr. Rose's work has already appeared in *Nuclear Engineering*, December, 1958, p. 523, in the form of an article "Pressure Vessel Nozzle Design—A New Approach to Reinforcement.")

It must be borne in mind that this symposium was not specifically "tailored" for the nuclear field so that, while parts of it (such as Papers 3 and 7) are of specific application, other facets are of more general interest. While, for example, the nuclear industry is keenly interested in the problems of brittle fracture, it is not so concerned with the effects of continuous temperature or pressure cycling. In certain directions the symposium did not completely cover the problems of the nuclear field—in brittle fracture, for instance, where the transition temperatures of steel can be considerably altered by neutron irradiation. (This point was considered at some length by the Iron and Steel Institute's symposium in December last, briefly reported in these columns for January, 1961, p. 37.) Nevertheless, the majority of papers contained a great deal that was of vital importance to the nuclear industry and we echo the general demand for a revision of design codes at the earliest possible moment.

MEETINGS

March 1-2. The Institution of Mechanical Engineers (at 1 Birdcage Walk, London, S.W.1, 4.30 p.m.). Symposium on **User Experience of Large-Scale Industrial Vacuum Plant.**

March 3.—The Institution of Structural Engineers (Western Counties Branch, at the Small Lecture Theatre, University Engineering Laboratories, University Walk, Bristol, 8, 6 p.m.). **Berkeley Power Station—Some Special Factors Influencing Design and Construction.** A. L. Brake.

March 7.—The Institution of Chemical Engineers (at the Geological Society, Burlington House, London, W.1, 4 p.m.). Papers on **Fluidization.** From AERE, Harwell.

March 10.—The Society of Instrument Technology (Midland Section, at Gosta Green College of Technology, Aston Street, Birmingham, 6.30 p.m.). **Control Problems of Nuclear Power Stations.** R. B. Quarmby.

March 15.—The Society of Instrument Technology (Data Processing Section, London, at Manson House, 26 Portland Place, W.1, 6.30 p.m.). Symposium of Burst Slug Detection in Nuclear Power Stations. **Initial Experience on the Use of a Digital Computer for Burst Slug Detection.** J. L. W. Churchill and R. S. Hopkins. **Burst Slug Detection Data Display at Bradwell.** J. L. Joss.

March 21.—The Institute of Metals in conjunction with the B.N.E.C. (at Church House, Westminster, London, S.W.1, 2.30 p.m.). Discussion on **Compatibility Problems in Gas Cooled Reactors.**

March 22.—The Institution of Electrical Engineers (at Savoy Place, London, W.C.2, 5.30 p.m.). Lecture on **The Engineering Aspects of Plasma Physics.** R. Carruthers and D. L. Smart.

March 29.—The British Institute of Radio Engineers (at London School of Hygiene and Tropical Medicine, Keppel Street, Gower Street, London, W.C.1, 3 p.m.). Symposium on **Electronic Instrumentation for Nuclear Power Stations.**

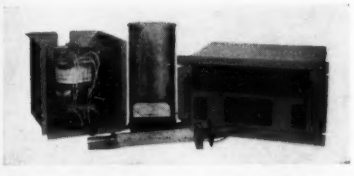
Processes and Equipment

For further information on any item please enter the relevant number on the Reader Service Card enclosed with this issue and forward the card to the address given.

Resistivity Meter for Liquid Metals

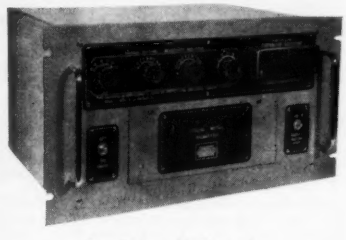
The importance of continuous checking of the oxygen content of sodium or NaK used as coolant scarcely needs emphasizing here; the build-up and clogging of circuits due to oxide formation is, by now, well known. Since the change in resistivity of NaK is about 100 ppm for an oxygen increase of 1 ppm, continuous measurement of resistivity in a branch of the main coolant loop would provide a convenient method of monitoring oxygen content.

There are, of course, many practical difficulties to be overcome. In addition to the extreme sensitivity required, the temperature errors provide a quite formidable obstacle, since the temperature coefficient of sodium is such that a change of resistivity of 100 ppm is produced by a temperature change of 0.04°C, i.e., the temperature error is more than comparable with the required measurement of impurity content.



General view of complete equipment, showing mumetal enclosure for transformer unit.

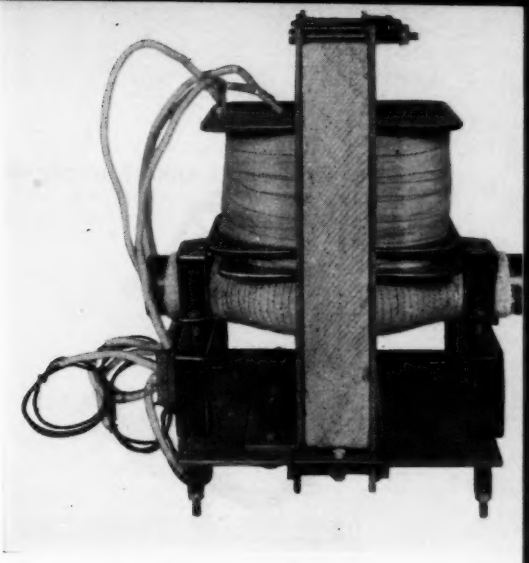
The development of a suitable type of instrument by the U.K.AEA for the Dounreay fast reactor has been described in an I.E.E. paper by Blake*. The most obvious method to pass a current through a section of the circuit and measure the voltage drop between two probe electrodes, using the Kelvin double bridge method, has many disadvantages, not the least of which is the error introduced by a by-pass current flowing around the " outside " of the circuit and, therefore, dependent upon the geometry of the loop and its temperature changes. The paper gives an account of the development of a potentiometric method using a current directly induced in the liquid metal by a transformer to induce a voltage in another transformer to effect the resistance measurement. There is a final design, now available commercially, manufactured under licence from the U.K.AEA.



Detail view of bridge unit.

Temperature compensation unit, showing liquid metal extension tube with comparator resistance winding.

In this design, the liquid metal flows through a stainless steel toroid surrounding the central limb of a shell type transformer which carries the " probe " winding as well, so that the two transformers are combined into one, as seen in the illustrations, the core being of mumetal, and the entire transformer being surrounded by a mumetal shield, to reduce the possibility of errors from stray fields.



Detail view of torus with transformer core and coils.

Temperature compensation is of paramount importance and is achieved by the use of a comparator resistance winding in the circuitry, this being composed of platinum (which has a temperature coefficient comparable with that of sodium) non-inductively wound round a section of the pipe carrying the liquid metal. A layer of 0·002 in mica interposed to give electrical insulation without introducing a long time-lag on changes in temperature. The potentiometer circuit operates, via matching transformer and phase-sensitive rectifier, a d.c. recorder. Oxygen concentrations as low as 1 ppm have been detected.

(Bruce Peebles and Co., Ltd. (Electronics Division), Edinburgh 5.)

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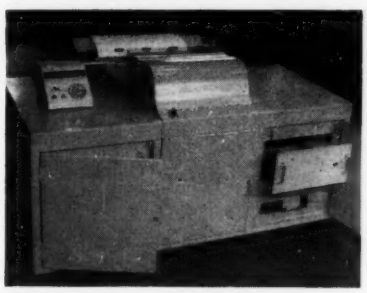
* " Resistivity Monitor to indicate oxide content of sodium." L. R. Blake, Ph.D., B.Sc., A.M.I.E.E. *Proceedings of the Institution of Electrical Engineers*, Vol. 107 Part A, No. 34 (August, 1960).

Data Scanning Equipment

The Bailey " Digilog " scanner has been developed for sequential scanning of data in analogue form, converting the signals to digital values, and printing out either a continuous series, with alarm signals when values depart from safe limits, or to print out only abnormal values. It can be equipped with a short-term tape memory, so that on the occurrence of abnormal conditions, all information for, say, the previous hour is available for reference. Facilities are also available for breaking-in on a scan, and obtaining a reading of one particular point, on a tube display unit, the reading being corrected on each subsequent scan.



Bailey " Digilog " equipment.

The Digilog is provided with its own form of chart drive and printing mechanism, the conventional electric typewriter being not considered sufficiently robust for continuous operation. Information can be presented in schematic form (e.g., diagonally) on the log sheet, if required.

(Bailey Meters and Controls, Ltd., Purley Way, Croydon, Surrey.)

1060

Intercommunication System

Intercommunication when working with pressurized suits requires freedom from extraneous noise, as well as ruggedness and reliability. A system designed primarily for the U.K.AEA, and now being generally marketed, combines all three features with the ability to set up either permanent or temporary networks for intercommunication between up to 10 " slave " sets and a master set.

Each wearer of a pressurized suit is equipped with a headset, having large rubber

Spembly individual equipment with headphones, boom microphone and transistorized amplifier and noise filter.

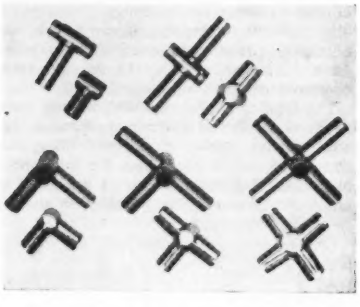
earpads, and a boom microphone. In the pocket is carried a small "personal" set, containing transistorized amplifier, volume control and noise-limiting circuits. The master unit consists of a control unit (using either a standard headset or plug-in microphone and loudspeaker, as required) and a mains-operated transistor-regulated power pack; in case of mains failure, a 12V battery may be used. By the use of a small battery junction unit an emergency network can be set up within a very short time independent of mains supply. A safety relay is provided in the control unit, in case of short-circuit or mechanical damage to any set.

(Spembly Limited, New Road Avenue, Chatham, Kent.)

1061

"Clinch" Tube Joints

Said to be stronger than the mating tubes themselves, a new type of joint known as "Clinch" is being marketed for rapidly assembling all types of tubular structures without bolting or welding. It can thus be applied in the exporting of tubular structures in knocked-down form, for assembly by unskilled labour, if required. Assembly



Typical "Clinch" units for tees, corners and 4- and 6-way cross joints.

is simple, it being only necessary to cut off tubes to length, slide the joint over one tube, and compress with a self-locking wrench to insert the sprung spigot stems into the mating tubes, and hammer home with a mallet. The finished joint has a neat appearance, as may be seen from the illustration, which shows angles, tees, and two- and four-way crosses. Obtainable at the moment for 1¼ in o.d. x 16 SWG ERW tube, they will shortly be available in other sizes.

(Access Equipment Ltd., Maylands Avenue, Hemel Hempstead, Herts.)

1062

Self-testing Amplifier

Main advantage of a new U.S. flux amplifier for providing reactor power level for logging control or shutdown, is a self-testing feature. Once per second, a 100 μ sec pulse of scram level is applied by a pulse generator, and registered by a monitor circuit at the trip output; if this pulse does not appear, warning signals are operated.

The amplifier, adjustable over a range of

G.E. self-testing flux amplifier.

10^{-7} A to 10^{-3} A, is said to have a zero drift of less than 0.5%, and to have a response time of less than 5 msec with 1 000 ft of cable to the ion chamber. It is of plug-in modular construction, with panel dimensions of 19 in × 7 in, and has a built-in solid state device producing 1 400 V for ion chamber activation.

(General Electric Atomic Power Equipment Department, San Jose, California.)

1063

Protection for Welders

The "Pulsafe" combination of hard hat and welding shield is designed to reconcile the need for protective headgear without the use of a hand-held welding screen. The shield, in moulded vulcanized fibre or glass fibre, is attached to a plastics hat in such a way that it is instantly detachable when required, or can be tilted upwards, a ratchet attachment preventing it falling back, so that inspection of work can take place without removing either. The glass shield is also fitted in a flip-up front, so that brief inspection, or chipping, may be carried out without even raising the shield.

The "Pulsafe" combined safety hat and welding shield.

(Safety Products, Ltd., Holmethorpe Avenue, Redhill, Surrey.)

1064

Dual-purpose Monitor

Intended for beta, gamma, and X-radiation of low and medium intensities, or alphas with energies as low as 4·5 MeV, the new Nuclear-Chicago type 2586-S gun-type survey meter is claimed to be the first to measure

Nuclear-Chicago dual-purpose monitor with interchangeable measuring heads.

BRIEFLY . . .

Alfred Bullows and Sons, Ltd., Long Street, Walsall, Staffs, announce the introduction of a range of activated charcoal filters for compressed-air systems. The range includes five models, with capacities of 3, 10, 30, 60 and 120 ft³/min. **B222**

A new r.f. induction heater, the E 9 ZS, has been introduced by **Delapena and Son, Ltd.,** Tewkesbury Road, Cheltenham, Gloucestershire. Of 9 kW output at 4-5 Mc/s, it is intended for zone refining and semi-conductor crystal growing. **B223**

Techne (Cambridge), Ltd., Duxford, Cambridge, are to manufacture a micro-tensile testing machine developed in the research laboratories of Tube Investments, Ltd. It will deal with single crystal whiskers down to 2×10^{-10} in² cross-section, and can be adapted for compression tests and tests in special atmospheres. Optical and mechanical measurements of extension can be made from a few Angströms to 15 mm. **B224**

Solid state particle detectors for X- and gamma-ray detection are being produced in sampling quantities by **Semi-Elements Inc.,** Saxonburg Boulevard, Saxonburg, Pennsylvania. Prototypes indicate that sensitivity can be directly compared with crystal-photomultiplier combinations; response time is not yet as rapid. **B225**

The Unique Slide Rule Co., Ltd., 400 South Coast Road, Telscombe Cliffs, Sussex, announce that their range of slide rules has been completely redesigned. Among the types produced are two "universal" models, a log-log, and a model specially designed for the chemical industry. **B226**

Failure of power supply to gamma radiation area monitors is prevented by an auxiliary power supply unit marketed by **Nuclear Measurements Corporation,** 2460 N. Arlington Avenue, Indianapolis, 18, Indiana. Known as the PSA-11, the unit contains a battery and charger unit which, in case of failure of the 110 V mains, will provide 8 hours' operation of the GA-2 gamma monitor, automatically recharging the batteries on restoration of supply. Dimensions are 20 in square x 6½ in deep. **B227**

CAEMCO (Controlled Atmosphere Enclosures Manufacturing Co.), P.O. Box 3693, Jacksonville 6, Florida, announce the availability of dry-box gloves in butyl. They are said to have less than one-tenth the permeability of conventional neoprene gloves. **B228**

An interesting sidelight on the article "Accelerators in Radiography (*Nuclear Engineering*, November, 1960, p. 517) is that the **High Voltage Engineering Corporation,** Burlington, Massachusetts, is constructing an 8 MeV linear accelerator for the A. O. Smith Corporation of Milwaukee. The output of this accelerator, due for completion this spring, is said to be 1 500 r/min with a 1 mm focal spot, or 6 000 r/min if the focal spot is increased to 5 mm diameter, the larger spot allowing radiography of 11 in thick steel in 1 min. **B229**

Interlas, Ltd., 9 Church Street, Ampthill, Bedford, are marketing the Terrier 600, a new welding electrode holder. Unlike many designs, the cable does not pass through the handle, so that this remains cool even on long runs using 5/16 in electrodes at 600 amp. **B230**

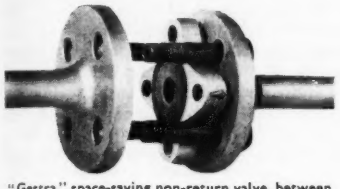
both dose-rate, and accumulated dose. This is achieved by interchange of two plug-in ion chambers. The integrating chamber gives five ranges of measurement, from zero to 0·25, 2·5, 25, 250, 2 500 mr respectively, the rate measurement has three ranges with maximum value of 25, 250 and 2 500 mr/h respectively. Energy dependence of either chamber is only ±4%.

(Nuclear-Chicago Corporation, 359 East Howard Avenue, Des Plaines, Illinois. Continental Distributors, Ltd., 121 Earls Court Road, London, S.W.5.)

1065

Space-saving Valve

Developed in Germany, the Gestra non-return valve is of the spring-loaded disc type, accommodated in a simple flange which can



"Gestra" space-saving non-return valve, between two pipe flanges.

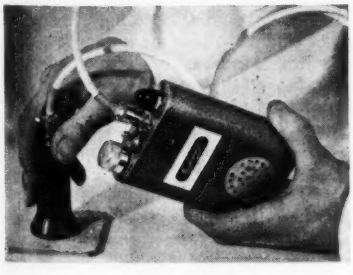
be inserted between two standard bolted pipe flanges, and takes up less than 10% of the length of a normally designed non-return valve. It is available in sizes from ¼ in-4 in, for pressures up to 460 psi, and temperatures up to 750°F.

(I.V. Pressure Controllers, Ltd., Atlas House, 683 London Road, Isleworth, Middlesex.)

1066

Compact Thickness Gauge

Rapid checking of the thickness of metal coatings is possible by the use of a new pocket-size unit developed by I.C.I. specifically for sprayed zinc or aluminium coatings of



Pocket-size gauge for rapid checking of coating thickness.

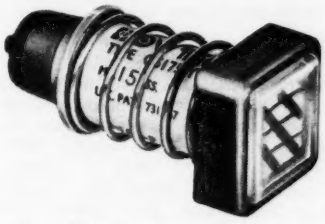
thickness of 0·002 in-0·012 in. Light in weight, transistorized, and operated from a built-in battery giving a life of about four months, the gauge is first calibrated against a standard test piece, and gives an audible warning when the exploring head reaches an area where the thickness of coating is less than the pre-set value. Adaptors will shortly be available for adapting the instrument to curved surfaces and tubes.

(Metallisation Limited, Barclays Bank Chambers, Dudley, Worcs.)

1067

Magnetic Indicator

A new three-position indicator for control panels or mimic diagrams has the advantage that it is, in effect, self-checking and failure of supply is immediately evident. The patterns are formed by movement of a number of prisms actuated by two solenoids.



(Above) Dowty 3-position magnetic indicator.

(Right) Dynatron timing unit mounted on the 1009 scaler.

One pattern is shown when the first solenoid is energized, another pattern when the second solenoid is energized. When both coils are de-energized, the third pattern is shown.

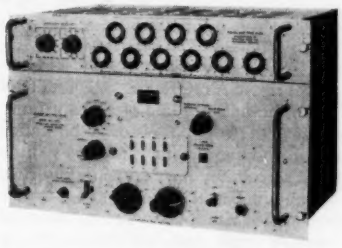
The units are small, the weight being 2·2 oz, and the display surface is ¾ in square. Life expectancy is said to be over 10^6 operations, and most stringent vibration tests have been applied. The consumption is 0·067 A at 28-30 V d.c.

(Dowty Electrics Ltd., Tewkesbury, Glos.)

1068

Dynatron Timing Unit

The type N108 timing unit has been designed primarily to operate with the



Dynatron Series 1009 scaling units, its main function being to switch off the scaler at either a preset time or a preset number of counts. It has a maximum time store of 100 000 sec, or a maximum count setting of 10^6 counts when used in conjunction with the 1009 scaler, which is enabled to operate at a resolution time of 1μs, thereby allowing a count rate of 200 kc/s. The timer can obtain its supplies from the scaler, and count and time totals are read from calibrated decade tubes.

(Dynatron Radio, Ltd., Maidenhead, Berks.)

1069

CATALOGUES

"British Instruments" is the title of the second edition of the Directory and Buyers Guide issued by the **Scientific Instrument Manufacturers' Association** in conjunction with **United Science Press, Ltd.,** Boswell House, 9 Gough Square, London, E.C.4. This combines the "British Scientific Instruments" and the "Instrument Directory and Buyers Guide" into a single publication of 636 pages, giving a complete picture of the instrument industry.

Albright and Wilson (Mfg.) Ltd., 1 Knightsbridge Green, London, S.W.1, have issued a new general chemicals catalogue.

Split field motors, tachogenerators, and ball-bearing gearheads are described in lists received from **Vactric (Control Equipment), Ltd.,** Vactric House, Sloane Street, London, S.W.1.

Aluminium pipe fittings and flanges for nuclear requirements are described in a catalogue produced by the **Svenska Metallverken Company,** Skultuna Division, Skultuna, Sweden.

A pocket pH meter powered by dry cells is described in a leaflet issued by the **Cambridge Instrument Co., Ltd.,** 13 Grosvenor Place, London, S.W.1.

Counters and Nobel load cells are described in leaflets received from **Ericsson Telephones, Ltd.,** Instrument Division, High Church Street, New Basford, Nottingham.

Miniature silicon rectifiers rated at 75-250 mA, 600-10 000 PIV, and miniature high-temperature rectifiers rated 300 mA, 1 500 PIV at 150°C, are described in leaflets from the **International Rectifier Company (Great Britain), Ltd.,** Hurst Green, Oxted, Surrey.

The January 1961 issue of *S.S. News*, published by **Solus-Schall, Ltd.,** County Building, Honeypot Lane, Stanmore, Middx, contains an article on the automatic ultrasonic testing of welds.

The use of nuclear moisture and density gauges is described in a folder received from **Nuclear-Chicago Corporation,** 359 East Howard Avenue, Des Plaines, Illinois.

"Thermoflash" water distillation plant is described in a publication received from **Bennis Thermoflash, Ltd.,** Little Hulton, Walkden, Manchester.

Tracerlab Inc., 1601 Trapelo Road, Waltham, Massachusetts, have issued a new products bulletin on liquid scintillation counting systems.

Valves for nuclear applications are the subject of a catalogue received from **J. Blakeborough and Sons, Ltd.,** Brighouse, Yorks.

Atomic Energy of Canada, Ltd., P.O. Box 93, Ottawa, Canada, have issued their catalogue "D" covering sealed sources, bulk isotopes, medical equipment and shipping containers; also included are particulars of their consulting and advisory service.

Radiation shielding windows are described in a leaflet from **Pilkington Bros., Ltd.,** St. Helens, Lancs.

A new price list of Sifbronze welding products has been issued by **Suffolk Iron Foundry (1920) Ltd.,** Sifbronze Works, Stowmarket, Suffolk.

The NMC gamma spectrometer is described in a publication from the **Nuclear Measurements Corporation,** 2460 North Arlington Avenue, Indianapolis 18, Indiana.

An intermediate size (500 W) laboratory oven and the "Torbal" precision balance are described in leaflets from **Baird and Tatlock (London), Ltd.,** Freshwater Road, Chadwell Heath, Essex.

Three new furnace publications dealing with the roller hearth type, hydrogen-atmosphere and induction furnaces have been received from **General Electric Co, Ltd.,** Erith, Kent.

Data sheets received from **Aircraft Porous Media, Inc.** (a subsidiary of Pall Corporation), 30 Sea Cliff Avenue, Glen Cove, New York, describe more than 200 standard element wire mesh filter assemblies.

Volume 12, number 2 of the *H.P. Journal*, published by the **Hewlett Packard Co.,** 1501 Page Mill Road, Palo Alto, California, describes a voltage-to-frequency converter for greater flexibility in data handling.

W. G. Pye and Co. Ltd., Granta Works, Cambridge, have issued a leaflet describing their new stabilized power supply unit.

A catalogue of "Cee Vee" remote handling equipment of various types has been received from **Carter and Viner,** Cooden Sea Road, Bexhill, Sussex.

Mallory electrical contacts are described in a 32-page publication recently issued by **Johnson, Matthey and Co. Ltd.,** 73/83 Hatton Garden, London, E.C.1.

Impalco aluminium and alloy extrusions are described in two catalogues, showing standard and selected sections, issued by the **Imperial Aluminium Co., Ltd.,** P.O. Box 216, Witton, Birmingham, 6.

"Some industrial uses of platinum metals" is the title of a booklet issued by **Engelhard Industries Ltd.,** Baker Platinum Division, 52 High Holborn, London, W.C.1.

Orbits . . .

MULTIPLICATION IS VEXATION ran the opening line of a chant familiar in what would nowadays be called our "formative years." (Today's little eggheads probably have some mildly rude rune about Bessel functions or matrix equations.) Multiplication lost most of it terrors with our discovery of log tables, and, later on, slide rules and—except for the minor detail that we still get the answers wrong—the manipulation of figures presents few difficulties.

What we do, sometimes, consider vexatious, is that multiple units are multiplying. Multiple units we must have—but some of them are getting out of hand. Early in our career we learned to cope with pounds-feet (*not* to be confused with foot-pounds), ounce-inches and, upon occasion, with gram- (spelt "gramme" in those unenlightened days) centimetres, as well as other units, some of which had names, and some didn't. This naming business seems to be a little bit arbitrary. If the British Thermal Unit had not been named a century or so ago, it would probably be called a "degree-poundef" while the calorie would probably rejoice in some such name as the "degree-gramec." Conversely, we have seen a plaintive query as to the necessity for a shortened form of a simple term such as the reactive-kilovolt-ampere-hour.

The point we are striving for (and it is bound to emerge if you wait long enough) is not whether to name units or not, but to determine which are "true" multiple units in that, as in the case of the foot-pound, they can be factorized in any proportion of the two ingredients, or the "fictional" type which is only useful for giving an overall idea. Amongst these, we would number the passenger-mile, the degree-day, and that supreme piece of fiction the man-hour, equally beloved by professional and amateur statisticians.

Mop-months and Man-rads

If Lewis Carroll were writing *Through the Looking Glass* nowadays, Alice would not have been subjected by the Walrus to meaningless queries about . . . "if seven maids with seven mops worked hard for half a year" . . ., etc. She'd have had some neatly-displayed figures in maid-mop-months under the heading of "Beach Clearance. Practicability of."

In our opinion, an even more useless unit than the mop-month has made its appearance. This is the man-rad, an integration of the individual radiation dosage of a number of men (or women, since the rad is fairly impartial and, nowadays it's very often difficult to tell the difference—except that women sometimes wear their hair shorter). Since the individual dose is the only thing that matters, the purpose of this unit is a little obscure. Yet a recent report makes a solemn comparison for U.K. AEA personnel, pointing out that although (due to increase in staff) the total man-rads have increased, the individual average dose is smaller. What does this prove? Well . . . strictly-between - ourselves - Christopher - Robin - and-don't-tell-a-soul, from where we're standing, it means that there's been a bigger increase in administrative staff (what the theatre calls "front of the house") than in the Working Classes.

"Vessels Large may Venture More . . ."

There can be little doubt that those attending the symposium on pressure vessel design, reviewed elsewhere in this issue, were generally, if not unanimously, of the opinion that design codes needed some revised thinking—and quickly. Quite apart from the handicap to overseas trade—in itself of vital importance—it appears that by using thicker plates than may be necessary, one may, in certain cases, be actively inviting trouble from brittle fracture.

The consequences of a vessel failure would be so catastrophic that were this scheme solely the offspring of a small group of advanced thinkers, one would hesitate to commend any undue haste. However, it is not; some of the best brains in industry are backing it. The question now arises . . . how is a change to be achieved?

Wanted: A Bogey Man!

The trouble is, paradoxically, that we are caught in the web of our own freedom. Like so many other British things, we are up against custom, not legal authority. The Factory Act in effect only says it must be safe; there is, for once, nothing for which the Government can be blamed. It is of no use the BWRA organizing the Abington Marchers, carrying banners reading "Ban BS 1500" to lie down in the street before Lloyd's. The only Goliath that this redoubtable band of Davids will find is the good old giant Inertia. Everybody (except the fine old crusted, who never really approved of the change from wrought iron and rivets anyway) will say that it's a Jolly Good Idea—for someone else to try.

Two-in-One

Idly chatting the other day about reduction of power station capital costs and, in particular, the savings made possible by the combination of the two reactor operating floors *à la* Sizewell, it was suggested that the logical step would be the merging of the reactors themselves. The production of a couple of gigawatts from one giant economy-size package is attractive, and we offer (at reasonable fees) our publicity slogan "Giga and Better!" to the first design accepted.

There are, however, several snags to be overcome before this pipe-dream could become reality, not least of which is the aforementioned necessity for new thinking on pressure vessel thickness—else we'll soon find ourselves building vessels out of plates that are virtually cubes. More important still, we've got to get some operating experience. Already the gas-cooled reactor has been extrapolated to over four times the output of original design—would a further doubling-up without operational experience be courageous or foolhardy? Finally, there is the question of availability; from the viewpoint of system operation, can one accept the risk of a comparatively minor trouble shutting down the entire station? It's not always clever (as the theatre manager said when watching the jugglers from the Pyrenees get jammed in a revolving door) to have all your Basques in one exit.

Academic Outlook

One of our more progressive seats of learning has recently issued a booklet relating to the avoidance of hazards due to radiation. The fourth paragraph is a bit of an eye-opener. It reads:—

> *It is important to avoid unnecessary radioactive contamination in laboratories, since experimental results may be invalidated.*

It would be grossly unfair to suggest that this is the underlying theme of the booklet which is, actually, an excellent piece of work and firmly lays down procedures for ensuring safety to both the experimenter and the innocent bystander. It is also grossly unfair to use a sentence out of context to give the impression that the scientific mind is only concerned with accuracy, and that suffering humanity can go pedal its bicycle. But the temptation is too much for us. . . .

Clouds of active iodine
Give a count-rate unforeseen
And results o'er which we've toiled
By your carelessness are spoiled.

As your red corpuscles bleach
Hear the Prof. begin to preach
ACCURACY's what we lack
Blow thee—and thy thyroids—Jack!

Careful, now, upon that plank
By the nitric acid tank
For . . . it might be rather hot
(Splash!—He's in it! Clumsy clot!)

As you blacken, fry and fizz
Won't the Prof. be in a tizz
For you'll put, without a doubt
All the pH figures out.

Care's essential, you'll agree
That is live at ten kV
Pray, do not be over-rash
(What has caused that vivid flash?)

As you crackle, snap and pop
Hear the lab-man blow his top
What a surge—oh, have a heart—
LOOK at this recorder chart!

MEMORANDUM
We can sweep up your remains
Or . . . just hose you down the drains
But—we can't erase your sin
You're the Error Creeping In.

Tangent

Patents Reviewed

These abstracts have been made from British Patent Specifications, complete copies of which can be obtained from the Patent Office, 25 Southampton Street, London, W.C.2, at 3s. 6d. each (including postage).

B.P. 840,789. Boiling water reactor. To: U.S. Atomic Energy Commission (U.S.A.).

An injection nozzle is used with each fuel tube of the reactor to introduce condensate or feed water into the tube, and to draw into the tube moderator water surrounding the tube. Thus the power production can be made variable which otherwise depends only on the size of the fuel tubes if the flow is entirely convective. An injection nozzle at the bottom of each fuel tube has the additional advantage of minimizing the tendency of steam formation outside the tube.

B.P. 840,857. Method of producing shaped bodies of beryllium. T. R. Barrett, G. C. Ellis, R. A. Knight. To: U.K. Atomic Energy Authority.

By sintering (at 1 150 to 1 250°C) beryllium powder of particle size not greater than 80 microns in a mould, without external pressure, e.g., around a central graphite core to produce tubes, or directly on to and around a ceramic fuel core. The bodies can be accurately machined.

B.P. 841,253. Nuclear reactor. J. G. Linhart. To: British Thomson-Houston Co., Ltd.

The reactor operates with a thermonuclear fusion reaction employing very light elements. An ionized light gas (hydrogen and/or its isotopes; mixtures of hydrogen and lithium) is subjected simultaneously to a magnetic field and to an oscillating electric field perpendicular to the magnetic field, the frequency being such as to produce cyclotron resonance of the gas ions.

B.P. 841,533. Method of cooling nuclear reactors. K. Diebner (Germany).

Mercury is used at high pressures with a gas or vapour (argon; nitrogen) which is chemically inert in the surroundings of the cooling system.

B.P. 841,545. Fuel elements for nuclear reactors. E. P. Hotchen. To: U.K. Atomic Energy Authority.

Nuclear fuel encased in a silica sheath, the sheathed fuel being contained in a block of solid moderator material.

B.P. 841,608. Method of preparing a fuel element. To: U.S. Atomic Energy Commission (U.S.A.).

Swaging an encapsulated ceramic material (UO_2 powder in a zirconium capsule).

B.P. 841,643. Manufacture of graphite artefacts. G. H. Greenhalgh. To: U.K. Atomic Energy Authority.

Applying pressure to natural graphite powder contained in a flexible polythene sheath through a fluid surrounding the sheath.

B.P. 841,792. Thermonuclear reactor. To: U.S. Atomic Energy Commission (U.S.A.).

Refers to the problem of initiating controlled nuclear fusion reactions. As the reaction rate is proportional not only to the particle energy, but also to the particle density the compression of a high energy plasma or space charge neutralized ion cloud will cause the desired reaction to proceed at a sufficient rate to produce more than enough energy to sustain itself. The invention contemplates the use of the pinch effect to provide the desired plasma compression. It further provides magnetic field means for deflecting plasma particles to produce an orbital path in the plasma.

B.P. 841,800. Vapour generating units for the recovery of heat from hot fluid under pressure. To: Babcox and Wilcox Ltd. (France).

A vertical pressure vessel is provided with an internal cylindrical partition to define a central gas pass connected with a surrounding annular gas pass. In the central gas pass are arranged vapour generating tubes longitudinally with respect to the gas flow. The annular pass contains an economizer with transversely arranged tubes wound in helical form about the central pass.

B.P. 841,972. Nuclear energy turbine. To: Esso Research and Engg. Co. (U.S.A.).

A gaseous medium (helium) containing fissile material (uranium hexafluoride) in a sub-critical condition is compressed to a critical degree and passed through a nuclear reaction zone containing sufficient moderator for a nuclear reaction in the medium to increase its enthalpy appreciably. The medium is then expanded in a turbine and recycled with its enthalpy thus reduced. The basic arrangement may comprise a compression zone in a first axial-flow gas turbine into which the working fluid passes to be compressed by the turbine blades to a critical degree reaching the nuclear reaction zone at about 900°C and 3,000 p.s.i. This zone may consist of a graphite block with a number of passageways and suitably distributed control rods. The heated fluid then enters an expansion zone which is a second axial-flow turbine on the same shaft and this turbine drives an electric generator as well as the first turbine. The medium is then recycled, e.g., through a heat exchanger, to generate steam for a conventional steam turbine.

B.P. 841,992. Nuclear reactors. S. A. Ghalib, G. E. Darwin, P. R. J. French. To: Metropolitan-Vickers Electrical Co., Ltd., British Thomson-Houston Co., Ltd.

The fuel elements are made in units of two or more laterally spaced (thin) plates of fuel material longitudinally arranged in hollow (rectangular) ducting of e.g. graphite for insertion in fuel passages. A number of such fuel units may be located in the reactor channels end to end.

B.P. 842,173. Fissile materials for nuclear reactors. A. Chitty. To: General Electric Co., Ltd.

A slurry of thoria in bismuth formed by agitating the mixture in an inert atmosphere in the presence of certain metals.

B.P. 842,317. Fuel elements for nuclear reactors. B. N. Watts, M. A. Cayless. To: British Thomson-Houston Co., Ltd.

A concentrated mass of material capable of absorbing or gettering large quantities of gas evolved from the fissile material, particularly hydrogen, is included in the fuel container.

B.P. 842,329. Nuclear reactors. J. S. Hollings. To: Rolls-Royce, Ltd.

The fuel element is formed by winding a sheet of clad uranium into a spiral the layers of which are held in spaced relation by rods inserted axially so as to form axial flow paths for the cooling fluid.

B.P. 842,330. Nuclear reactors. J. S. Hollings. To: Rolls-Royce, Ltd.

The bores for fuel elements through which the coolant fluid passes also provide paths for neutrons travelling lengthwise of these bores. In order to prevent or reduce escape of such radiation, spiral elements of neutron scattering material (graphite) are fitted in the ends of the bores.

B.P. 843,614. Gas discharge apparatus. P. A. Davenport. To: U.K. Atomic Energy Authority.

This refers to thermonuclear reactors with a high current ring discharge in a gas contained in a torus as described in B.P. 830,252. (*Nuclear Engineering*, Sept., 1960, p. 424). Two circumferential gaps are provided in the wall of the torus for constructional reasons and also to prevent the torus acting as a short-circuited turn. If exposed to bombardment by ions and/or photons from the gas discharge, these insulating gaps would break down with voltages less than 100 V across them. Therefore a liner system is provided in the torus to shield the gaps from the discharge. The annular space between the liner and the torus is, at least partially, sealed so that the space within the liner can be evacuated independently of the annular space between the liner and the torus, where the pressure may be arranged so as to inhibit the tendency for the gap to break down. The annular space may have a lower pressure than the space within the liner. Or, if the sealing is gas-tight, the pressure may be higher or open to atmosphere.

B.P. 843,615. Gas discharge apparatus. P. C. Thonemann. To: U.K. Atomic Energy Authority.

This refers to the liner arrangement in an apparatus as described in B.P. 830,252. The liner is electrically continuous around its large circumference and has a resistance around this circumference which is large compared with the resistance of the discharge.

B.P. 843,681. Nuclear reactors. To: Babcock and Wilcox, Ltd. (Germany).

Refers to coolant guiding means which effect flow of the coolant in series through a number of concentric passes progressing from the centre of the core towards the periphery so as to maintain the sheaths of the fuel elements at approximately the same temperature.

B.P. 843,730. Method of screening-off the radiation from nuclear reactors. K. Diebner (Germany).

The reactor is surrounded by a hollow structure filled with "Raschig rings" (short thin-walled metal tubes of equal height and diameter) and a hydrogen-containing fluid. The structure may be split into two or more zones, by a metal partition. Thus the reactor's combined gamma and neutron radiation will encounter not only substances of high atomic weight but also hydrogen atoms. The combination is effective for each of the two types of radiation.

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